# 10.5 COMPARISON OF POTENTIAL TEMPERATURE GRADIENT ESTIMATES FROM VARIOUS TEMPERATURE PROFILE DATA SOURCES

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## 1. INTRODUCTION

From July through September 2015, concurrent and collocated measurements of temperature profiles from two passive radiometers and a RADAR-RASS (Radio Acoustic Sounding System) were made at a site near the ocean just to the west of Los Angeles International Airport (LAX). This site is managed by the South Coast Air Quality Management District (SCAQMD). Temperature profiles for the same time period from NOAA's Rapid Refresh (RAP) hourly-updated assimilation/modeling system were included in the collection of profile data. For all temperature profiles a standard algorithm was used to convert temperature to dry potential temperature (PT). Data acquired at times when there was precipitation or fog were discarded. Humidity effects were not considered. It is important to note that all sensors were well maintained during the data acquisition period and that the ground based remote temperature profiling instruments involved were not part of data assimilation for RAP.

The motivation for this data collection effort was the idea that intercomparisons of the data obtained from the various temperature profiling sources could be used to characterize the variability of potential temperature gradient (PTG) values. It was felt that such a study would be a useful contribution to aircraft wake turbulence R&D because PTG (along with atmospheric turbulence, wind and various aircraft parameters) is identified in the open literature as a key factor in determining the temporal and spatial evolution of wake turbulence. Note that PTG is directly related to atmospheric stability.

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See Reference List A for studies on temperature profile comparisons (note – At present the authors are not aware of studies on PTG comparisons), and see Reference List B for current literature on how stratification affects trailing vortex evolution.

The current effort is focused on PTG comparisons at an altitude of 250m because this level is representative for out of ground effect wake turbulence consideration. An estimate of this quantity may be obtained from the difference between PT measured at approximately 200m and 300m.

The observed scatter of PTG intercomparisons can be used as a practical way of quantifying the variability in measurements of PTG at 250m. This information is important for understanding the variability of aircraft wake vortex data as well as for providing bounds on the variability of the environmental data used for wake modeling. This effort is an integral part of the Federal Aviation Administration's ongoing effort to examine and prototype additional weather based dynamic wake turbulence separation concepts.

## 2. DATA SOURCE DETAILS

The radiometers were a Model MP-3000A from Radiometrics Corporation and a Model MTP-5 PE from ATTEX and supplied by Kipp & Zonen USA, Inc. The MP-3000A uses 12 channels in the ranges 22-30 GHz and 51-59 GHz and acquires data along three different sight lines: vertical, 15deg N of vertical and 15deg S of vertical. For this study, the data from the 15deg north-of-zenith sky view was used because the portion of the sky seen in this way was close to the portion scanned by the MTP-5 PE. The vertical resolution of the MP-3000A profiles is 50m between altitudes of 0m and 500m and 100m between 500m and 1000m. Profiles were produced every ten minutes, but only hourly profiles were used in the comparisons for consistency with the other data sources.

The MTP-5 PE uses a single channel operating at a frequency of 60 GHz (5mm wavelength) scanning from 0deg to 90deg elevation. For this study it scanned towards the northwest. It produces vertical temperature profiles by measuring atmospheric thermal radiation in the center of the oxygen absorption band. A computational inverse method is employed to convert raw brightness temperature data to a vertical profile of temperature. The profile resolution is 10m from altitudes of 0m to 100m, 25m from 100m to 200m, and 50m from 200m to 1000m. Profiles are produced every five minutes, but as with the MP-3000A, only hourly profiles were used in the comparisons for consistency with the other data sources.

Note that the MP-3000A and MTP-5 PE temperature profiles are inherently smoothed as a result of the computational inversion processes that produce the profiles from the raw radiometer data.

The RADAR-RASS instrument, Model LAP3000 from Scintec, operated at 915 MHz with a narrowband acoustic source frequency close to 2 KHz. It produced virtual temperature profiles with a resolution of about 62m between altitudes of 174m and 985m. The RASS data were smoothed with a 100m boxcar filter to eliminate higher wavenumber noise. Ten minute averaged virtual temperature profiles were produced once per hour. Since the effort focuses on the vertical gradients of PT, the virtual temperatures were treated as if they were non-virtual temperatures. Resulting errors in the gradients were estimated to be on the order of 1-2%.

Temperature profiles from RAP data were used as if they were measured by an actual sensor. In fact, RAP profiles agree reasonably well with profiles from ACARS (Aircraft Communications Addressing and Reporting System) data which are measured by temperature sensors aboard departing and arriving aircraft. This agreement is shown in Appendix A for morning and afternoon time periods on two days in each of the three months of the deployment. The profile resolution for the RAP data was about 30m and the altitudes near 250m at which PT was reported were 190m, 221m, 251m, 282m and 312m.

Note that times for all data are converted to local standard time (PST) for analysis. Also note that quality control resulted in the elimination of a small amount of data.

**3. DATA COMPARISONS**

Potential temperature gradient (PTG) variability was determined by analyzing pairwise scatter plots of PTG from the various data sources. For each month (July, August and September) there were six scatter plots to examine. The RMS difference and average absolute difference between the data points for the various data pairs were the measures used to determine the variability of PTG. $R^2$ values from linear fits to the scatter plots were also computed.

Prior to the production and analysis of the scatter plots, time series plots of ground level MTP-5 PE and MP-3000A, and LAX ASOS temperature data were compared to ensure that the times for the data were in agreement. Note ASOS stands for Automated Surface Observing System, the temperature sensor for which is about 2m above ground.

From this point on, the data sources will be identified as DS1, DS2, DS3 and DS4. This is done to focus attention on PTG measurement variability rather than on individual data source performance.

Appendix B shows eight plots of PTG data. First, there is a time series plot of PTG from all four data sources for the month of July 2015. Then there are six pairwise scatter plots (DS1 vs DS2, DS1 vs DS3, DS2 vs DS3, DS1 vs DS4, DS2 vs DS4 and DS3 vs DS4) of the PTG data shown in the time series plot, and these are followed by a plot of the PTG data distributions for all four data sources.

Appendices C and D contain similar sets of eight plots for the months of August and September.

Shown on the scatter plots are summary statistics for the pairwise data comparisons. These statistics are RMS difference, absolute difference and the percent of data showing data points having absolute difference less than one. Also shown is the equation of the linear fit to the data and the $R^2$ value for the linear fit. Following are summary tables for the RMS, absolute difference, and $R^2$ statistics shown on the scatter plots.

## RMS Differences (degC/100m) ( <0.7 magenta )

| | DS1 vs DS2 | DS1 vs DS3 | DS2 vs DS3 | DS1 vs DS4 | DS2 vs DS4 | DS3 vs DS4 |
|---|---|---|---|---|---|---|
| JUL/250 | 0.730 | 0.560 | 0.810 | 0.393 | 0.842 | 0.633 |
| AUG/250 | 0.718 | 0.736 | 1.103 | 0.817 | 1.061 | 1.037 |
| SEP/250 | 0.890 | 0.660 | 1.171 | 0.489 | 1.042 | 0.556 |

## Average Absolute Differences (degC/100m) ( <0.5 magenta )

| | DS1 vs DS2 | DS1 vs DS3 | DS2 vs DS3 | DS1 vs DS4 | DS2 vs DS4 | DS3 vs DS4 |
|---|---|---|---|---|---|---|
| JUL/250 | 0.579 | 0.436 | 0.656 | 0.305 | 0.639 | 0.487 |
| AUG/250 | 0.552 | 0.557 | 0.824 | 0.589 | 0.811 | 0.787 |
| SEP/250 | 0.685 | 0.491 | 0.889 | 0.376 | 0.803 | 0.423 |

## $R^2$ Values ( > 0.7 magenta, < 0.5 green)

| | DS1 vs DS2 | DS1 vs DS3 | DS2 vs DS3 | DS1 vs DS4 | DS2 vs DS4 | DS3 vs DS4 |
|---|---|---|---|---|---|---|
| JUL/250 | 0.448 | 0.624 | 0.358 | 0.749 | 0.363 | 0.587 |
| AUG/250 | 0.724 | 0.855 | 0.701 | 0.468 | 0.348 | 0.379 |
| SEP/250 | 0.551 | 0.781 | 0.527 | 0.753 | 0.409 | 0.743 |

The RMS table shows that an upper bound for the sensor-to-sensor PTG differences is approximately one degC/100m (equivalent to a Brunt–Väisälä frequency of about 0.02 rad/sec). This observation implies that there should be allowance for an uncertainty of this amount for any measurement of PTG.

The range of $R^2$ values shown in the $R^2$ table varies from 0.348 to 0.855, which implies that the sensor-to-sensor measurements of PTG are at times weakly correlated. Furthermore, whenever $R^2$ is low, the difference values are high. In particular, if the $R^2$ values are directly compared with the difference values, it can be seen that whenever $R^2 < 0.5$, the RMS values are > 0.7 and the absolute difference values are > 0.5.

The PTG data distribution plots show that although there is a one degC/100m uncertainty in the PTG measurements and weak correlation between the sensor-to-sensor PTG measurements, the range of the PTG measurements for PTG > 0 (which is most relevant for the wake turbulence application) for the various sensors was consistent.

## 4. Model Results

In order to show the effect that the above observed PTG uncertainty of one degC/100m may have on the evolution of trailing vortices, the effect of this uncertainty on fast-time model results was examined. Three fast-time models were chosen to do the model runs, and each model was run three times. The parameters for the three cases run by each model differed only in the value of PTG, which was set to 1, 2 and 3 degC/100m in order to illustrate the effect due to a PTG difference of one degC/100m.

The fast-time models chosen for the model runs were selected to be representative (but by no means exhaustive) of the current international state-of-the-art. These models were based on DLR's D2P, NASA's TDAWP and NASA's APA v3.8. They were not the official model releases from their respective organizations, but were coded from open literature sources (see Reference List C), and are used herein only for illustrating the effect of the PTG measurement uncertainty.

The parameters for the model runs were as follows:

<u>Environmental Parameters:</u>

EDR = 1.e-4 $m^2/sec^3$
Zero wind
Variable PT Gradient (1-3 degC/100m)

<u>Aircraft Parameters:</u>

$B_0$ = 50m
$V_0$ = 2m/sec
$\Gamma_0$ = 628$m^2$/sec
$Z_0$ = 400m

Here EDR is eddy dissipation rate. $B_0$, $V_0$, $\Gamma_0$ and $Z_0$ are the initial separation distance, descent speed, circulation, and altitude of the vortices. The values chosen are not representative of any particular aircraft.

Results for the model runs are shown in Appendix E. If the model results at 120 sec are averaged, then it may be concluded that a one degC/100m variation in PTG can give rise to an uncertainty in circulation of 43 $m^2$/sec and an uncertainty in descent distance of 43m at that time. For practical considerations, these values can be rounded up to 50 $m^2$/sec for circulation and 50m for descent distance.

In the above discussion, DLR stands for Deutsches Zentrum für Luft- und Raumfahrt which is the German Aerospace Center, D2P stands for Deterministic Two Phase, TDAWP stands for TASS Driven Algorithms for Wake Prediction (TASS is Terminal Area Simulation System, a Large Eddy Simulation code), and APA stands for AVOSS Prediction Algorithm where AVOSS is Aircraft VOrtex Spacing System).

## 5. Conclusions

The present profile comparison exercise suggests that PTG measurements derived from various data sources for PTG > 0 (which is most relevant for the wake turbulence application) are mostly consistent and that they indicate an uncertainty in the measurement of PTG of about one degC/100m. This implies that it may not be possible to measure PTG to much better than a tolerance of that amount. Fast-time model results show that the effect of this PTG uncertainty, for the example provided, can result in vortex circulation and descent uncertainties of 50 $m^2$/sec and 50m, respectively.

**Acknowledgements**
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**Reference List A**
Papers that report comparisons of temperature profile data (Note that none of these studies nor any others that the present authors are aware of consider potential temperature gradients). The papers are listed in reverse chronological order.

Friedrich, K., J.K. Lundquist, M. Aitken, E.A. Kalina and R.F. Marshall, 2012: Stability and turbulence in the atmospheric boundary layer: A comparison of remote sensing and tower observations, *Geophys. Res. Let.*, Vol. 39, L03801, doi:10.1029/2011 GL050413.

Drue, C., T. Hauf and A. Hoff, 2010: Comparison of boundary-layer profiles and layer detection by AMDAR and WTR/RASS at Frankfurt Airport, *Boundary-Layer Meteorol.* 135:407-432, doi: 10.1007/s10546-010-9485-0.

Argentini, S., I. Pietroni, C. Gariazzo, A. Conidi, G. Mastrantonio, A. Pelliccioni, I. Petenko, A. Viola and A. Amicarelli, 2008: Temperature profiles by ground-based remote sensing and in situ measurements, IOP Conf. Series: Earth and Environmental Science, doi: 10.1088/1755-1315/1/1/012025.

Benjamin, S.G., B.E. Schwartz and R.E. Cole, 1999: Accuracy of ACARS wind and temperature observations determined by collocation, *Weather and Forecasting*, Vol. 14, Dec, 1032-1038.

Westwater, E.R., Y. Han, V.G. Irisov and V. Leuskiy, 1999: Remote sensing of boundary layer temperature profiles by a scanning 5-mm microwave radiometer and RASS: comparison experiments, *J. Atmos. and Ocean. Tech.*, Vol. 16, July, 805-818.

**Reference List B**
Papers that address the effect of stratification on trailing vortex evolution. The papers are listed in reverse chronological order.

Holzäpfel, F., 2014: Effects of environmental and aircraft parameters on wake vortex behavior, *Journal of Aircraft,* 51, 1490-1500, September – October.

Pruis, M.J. and D.P. Delisi, 2011: Assessment of fast-time vortex prediction models using pulsed and continuous wave lidar observations at several different airports, AIAA Paper 2011-3035, June.

Holzäpfel, F., T. Gerz, and R. Baumann, 2001: The turbulent decay of trailing vortex pairs in stably stratified environments, *Aerosp. Sci. Technol.* 5, 95-108.

Neuhart, D.H., G.C. Greene, D.R, Satran, G.T. Holbrook, 1986: Density stratification effects on wake vortex decay, *Journal of Aircraft*, 23, 820-824.

Sarpkaya, T., 1983: Trailing vortices in homogeneous and density-stratified media, *J. Fluid. Mech.* 136, 85-109.

**Reference List C**
Papers that describe the fast-time models.

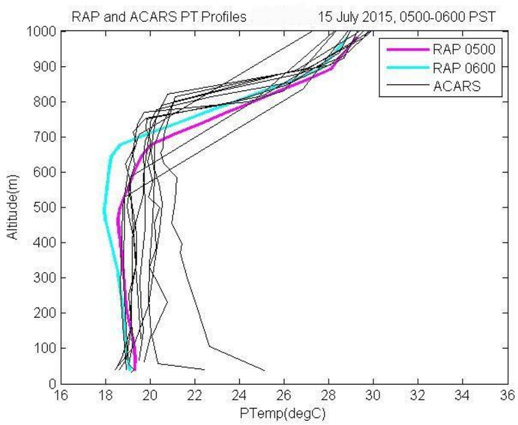
**D2P:**
Holzäpfel, F., 2003: Probabilistic two-phase wake vortex decay and transport model, *Journal of Aircraft*, 40, 323-331, March-April.

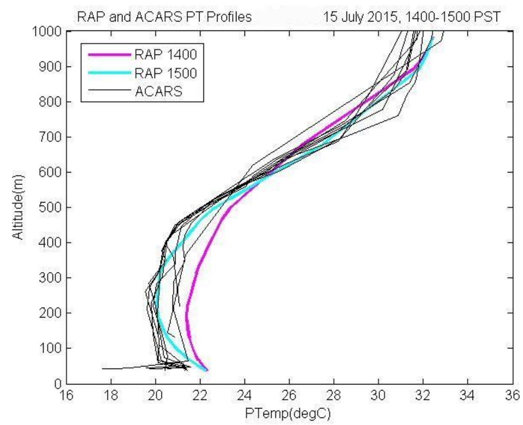
**TDAWP:**
Proctor, F.H., D.W. Hamilton, and G.F. Switzer, 2006: TASS driven algorithms for wake prediction, AIAA Paper 2006-1073, 44th Aerospace Sciences Meeting, January.

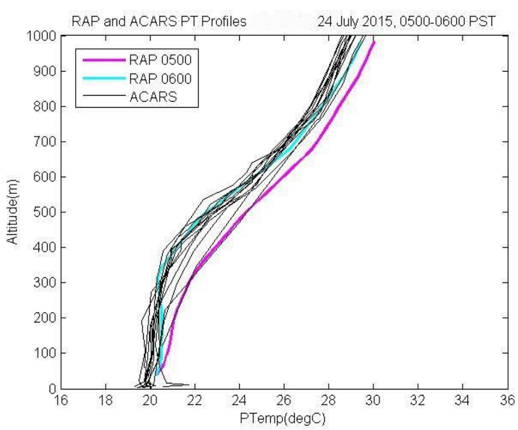
**APA v3.8:**
Delisi, D.P., R.E. Robins, and M.J. Pruis, 2016: APA 3.8 fast-time, numerical wake model description and first results, AIAA Paper 2016-3437, 8th Atmospheric and Space Environments Conference, June.

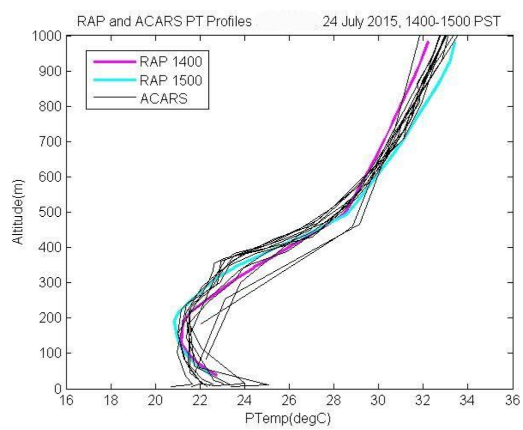
## Appendix A. Demonstration of Agreement between RAP and ACARS Data

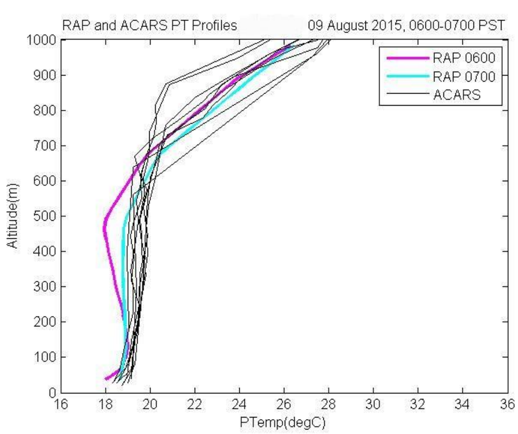
The following comparisons between RAP and ACARS data show that RAP data generally can be used as a surrogate for ACARS data. One reason for the good comparisons is that ACARS data is used as one of the inputs for the RAP model runs.

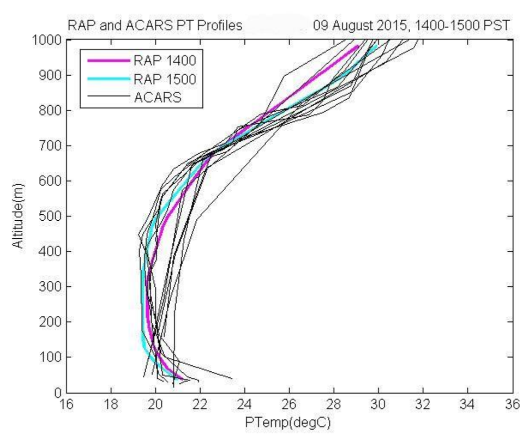


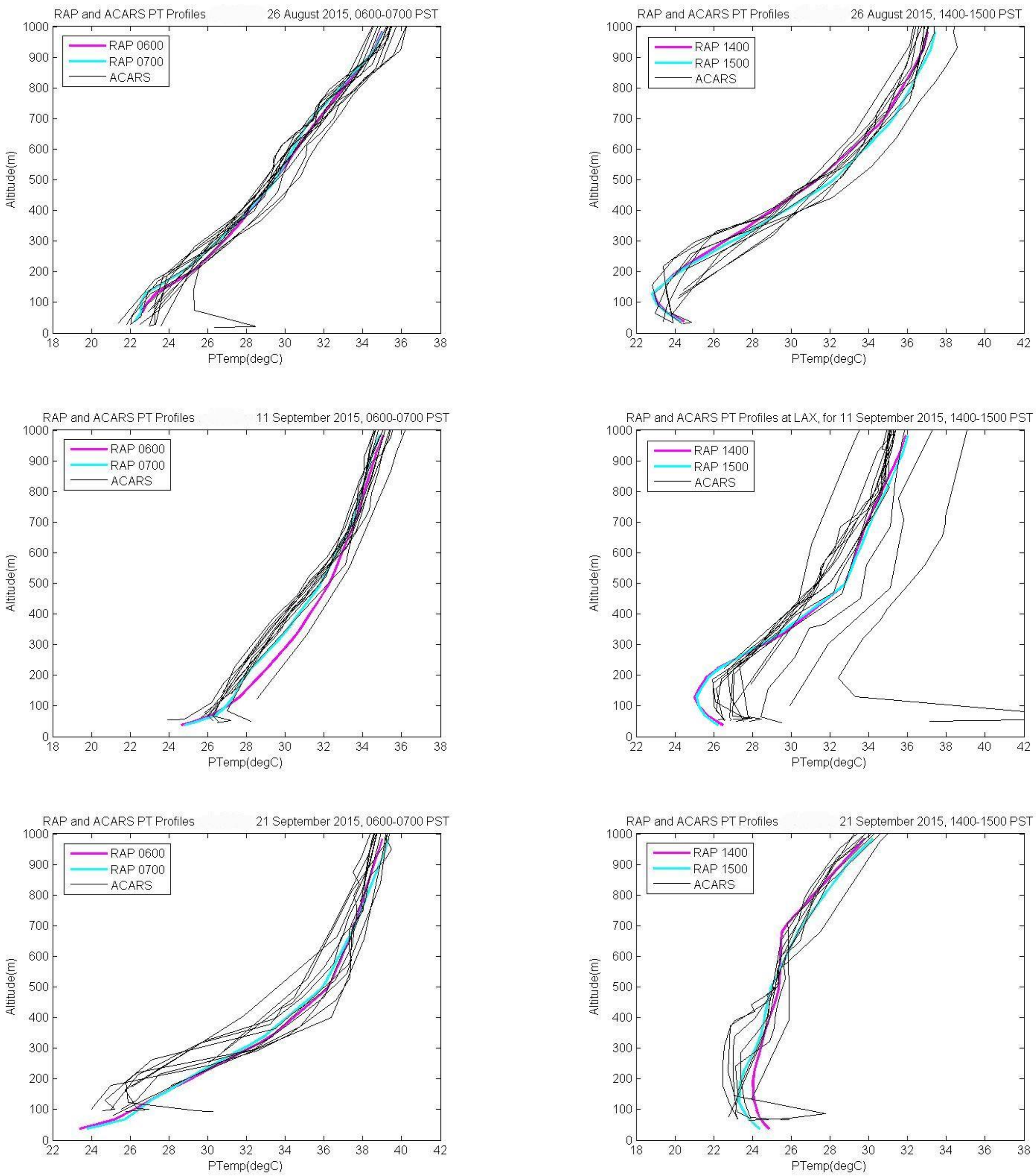



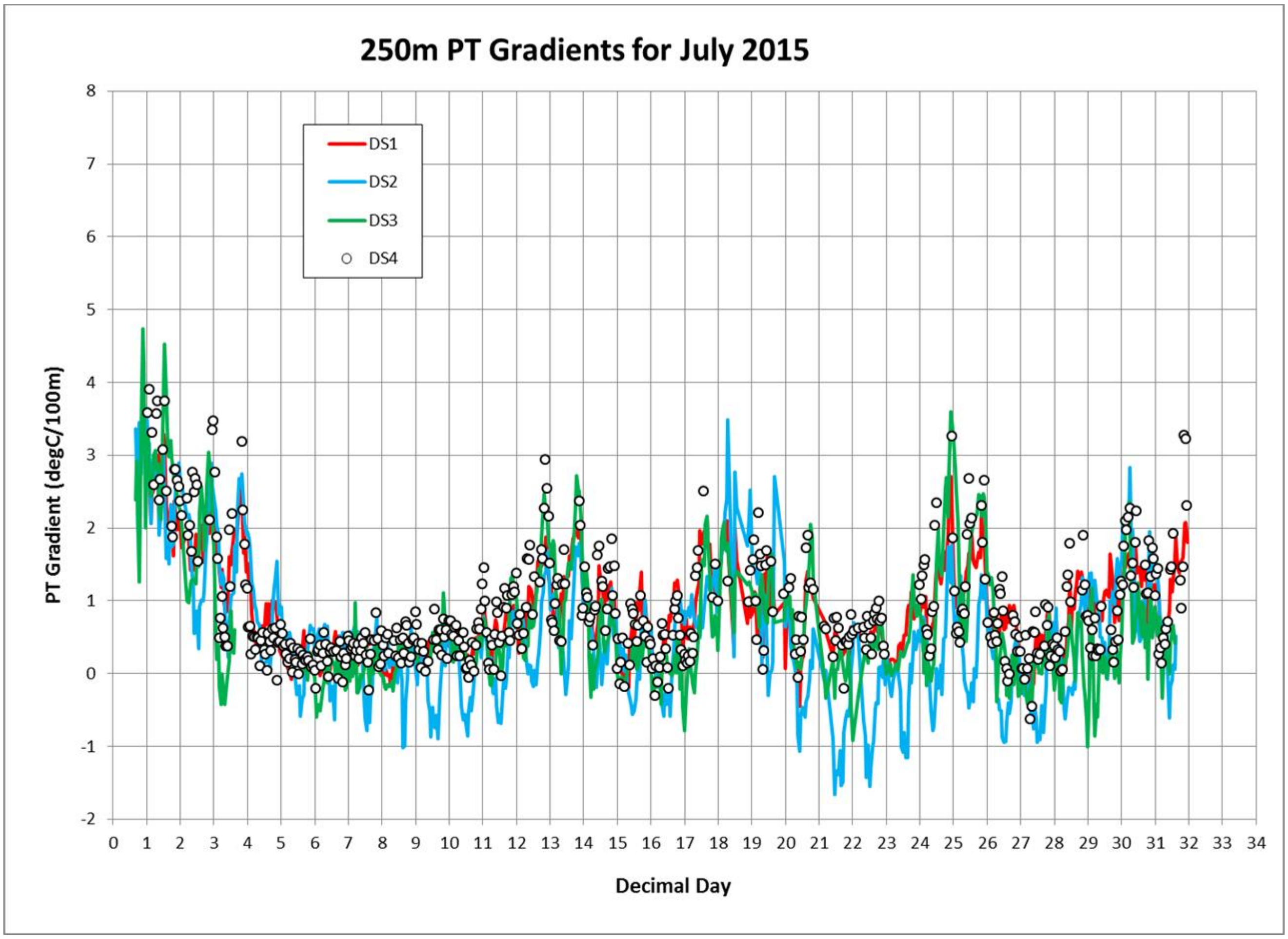



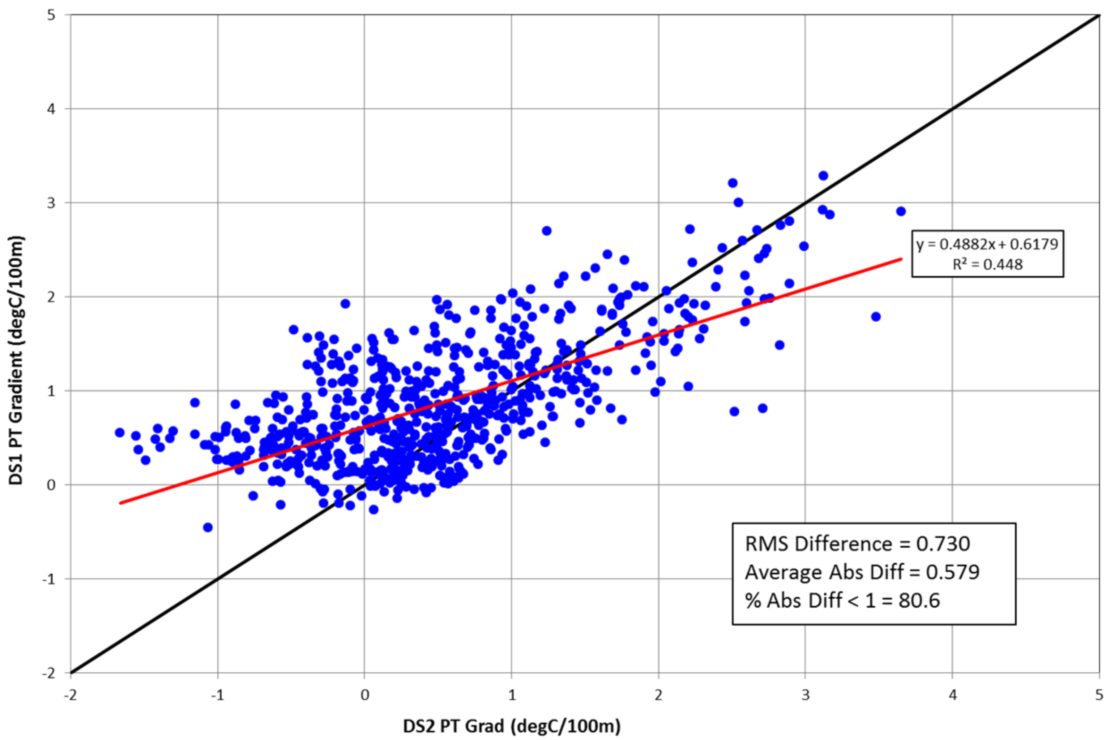




RAP and ACARS PT Profiles
26 August 2015, 0600-0700 PST
RAP 0600
RAP 0700
ACARS
Altitude(m)
PTemp(degC)
RAP and ACARS PT Profiles
26 August 2015, 1400-1500 PST
RAP 1400
RAP 1500
ACARS
Altitude(m)
PTemp(degC)
RAP and ACARS PT Profiles
11 September 2015, 0600-0700 PST
RAP 0600
RAP 0700
ACARS
Altitude(m)
PTemp(degC)
RAP and ACARS PT Profiles at LAX, for 11 September 2015, 1400-1500 PST
RAP 1400
RAP 1500
ACARS
Altitude(m)
PTemp(degC)
RAP and ACARS PT Profiles
21 September 2015, 0600-0700 PST
RAP 0600
RAP 0700
ACARS
Altitude(m)
PTemp(degC)
RAP and ACARS PT Profiles
21 September 2015, 1400-1500 PST
RAP 1400
RAP 1500
ACARS
Altitude(m)
PTemp(degC)

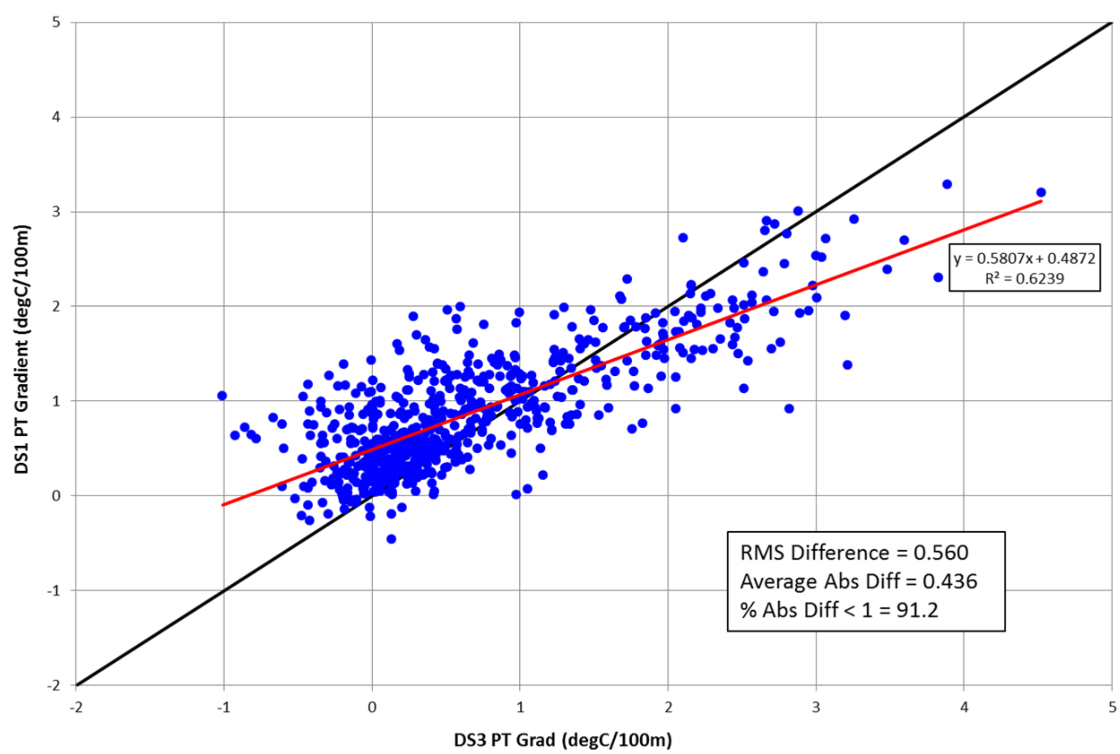
**Appendix B. PTG Plots for July 2015**

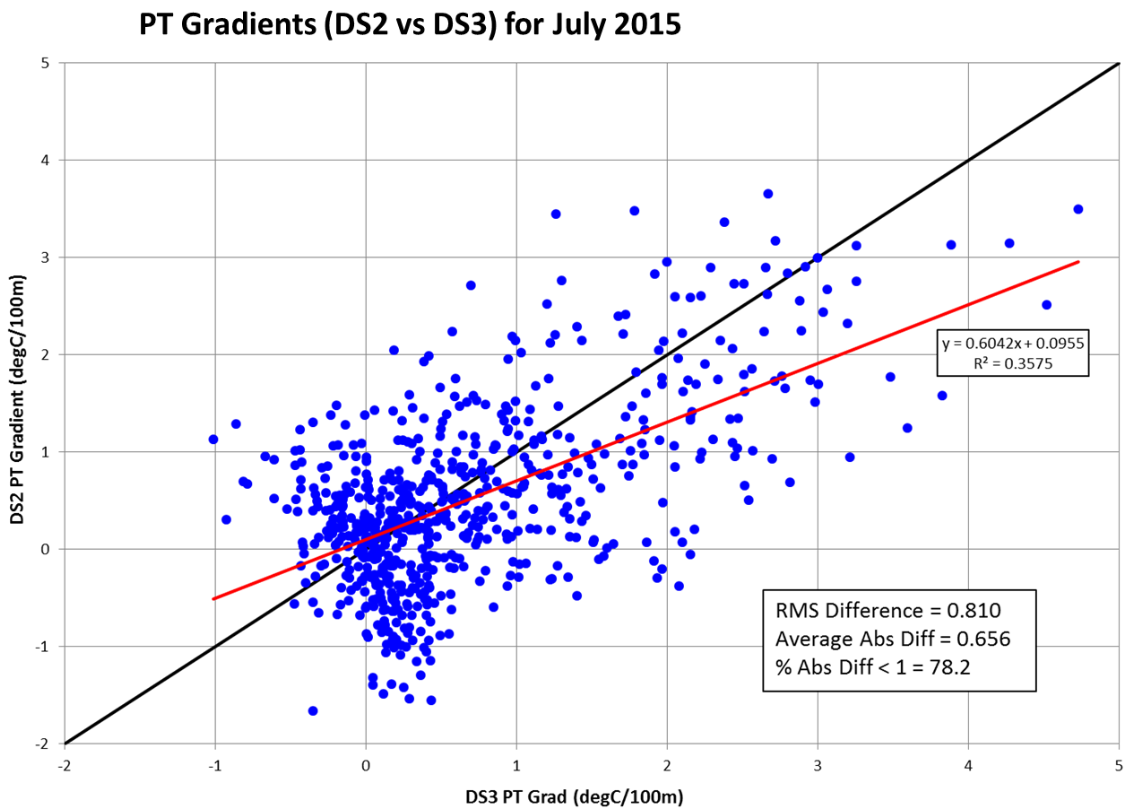


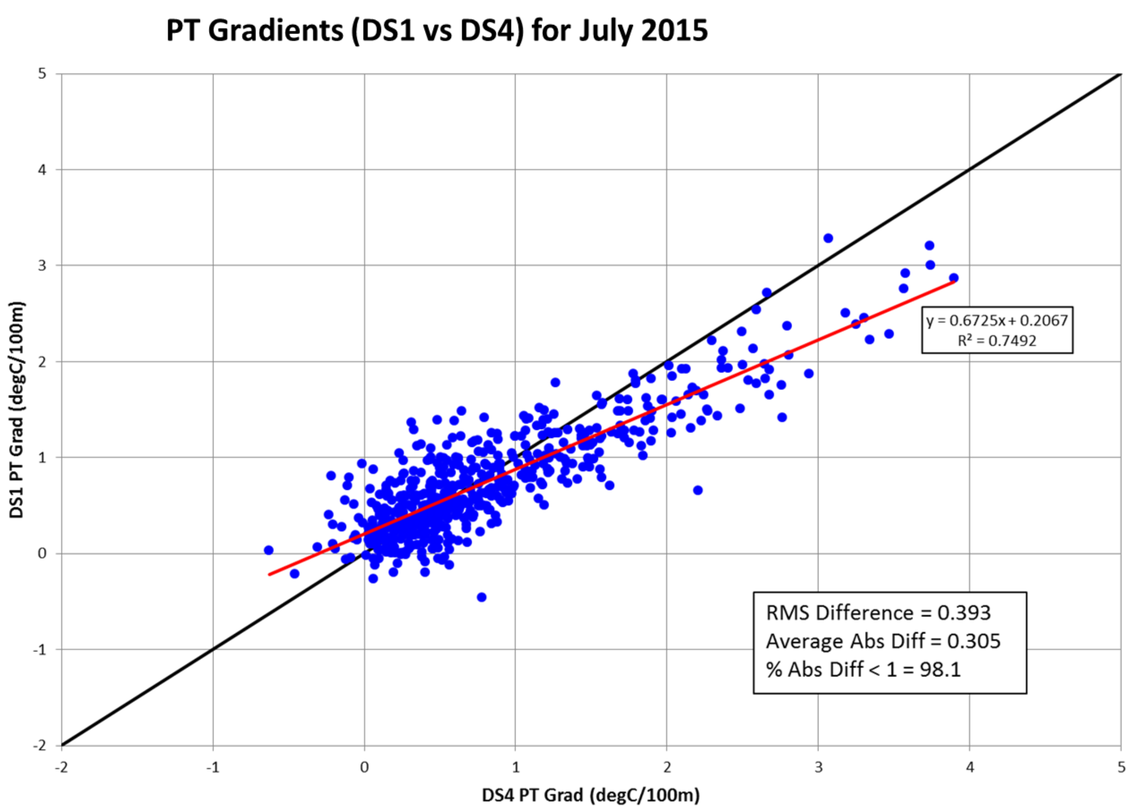
## PT Gradients (DS1 vs DS2) for July 2015

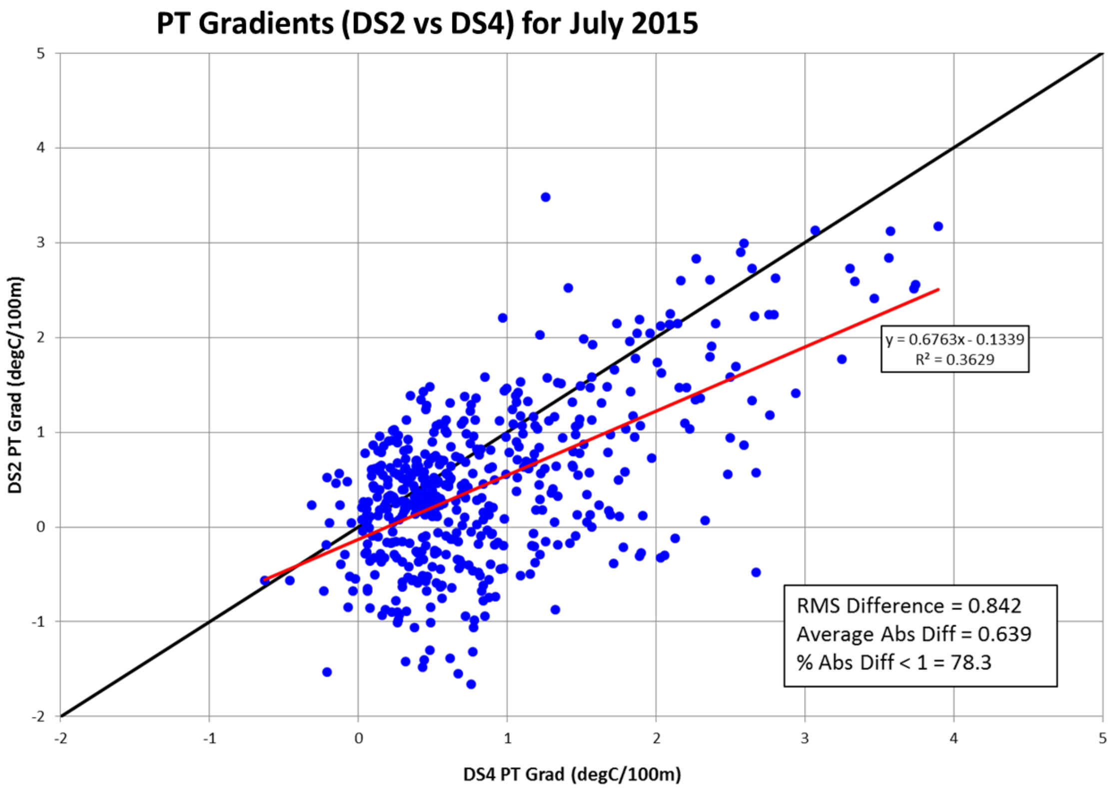


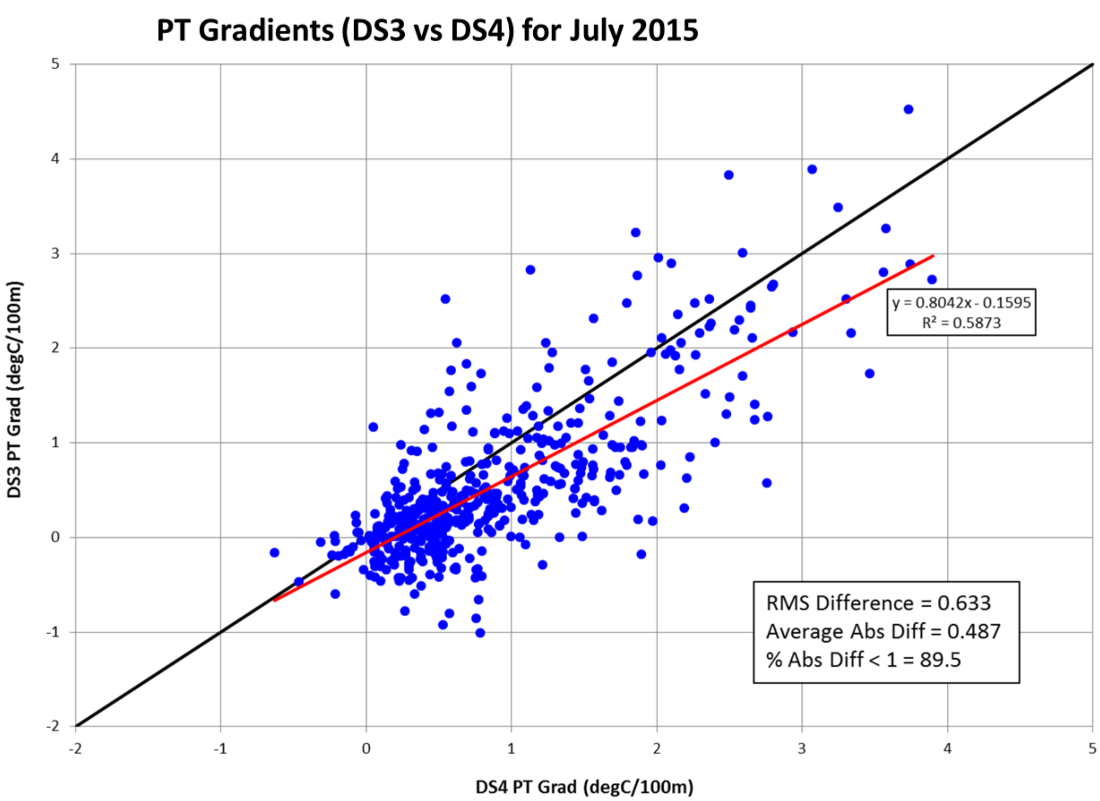

## PT Gradients (DS1 vs DS3) for July 2015

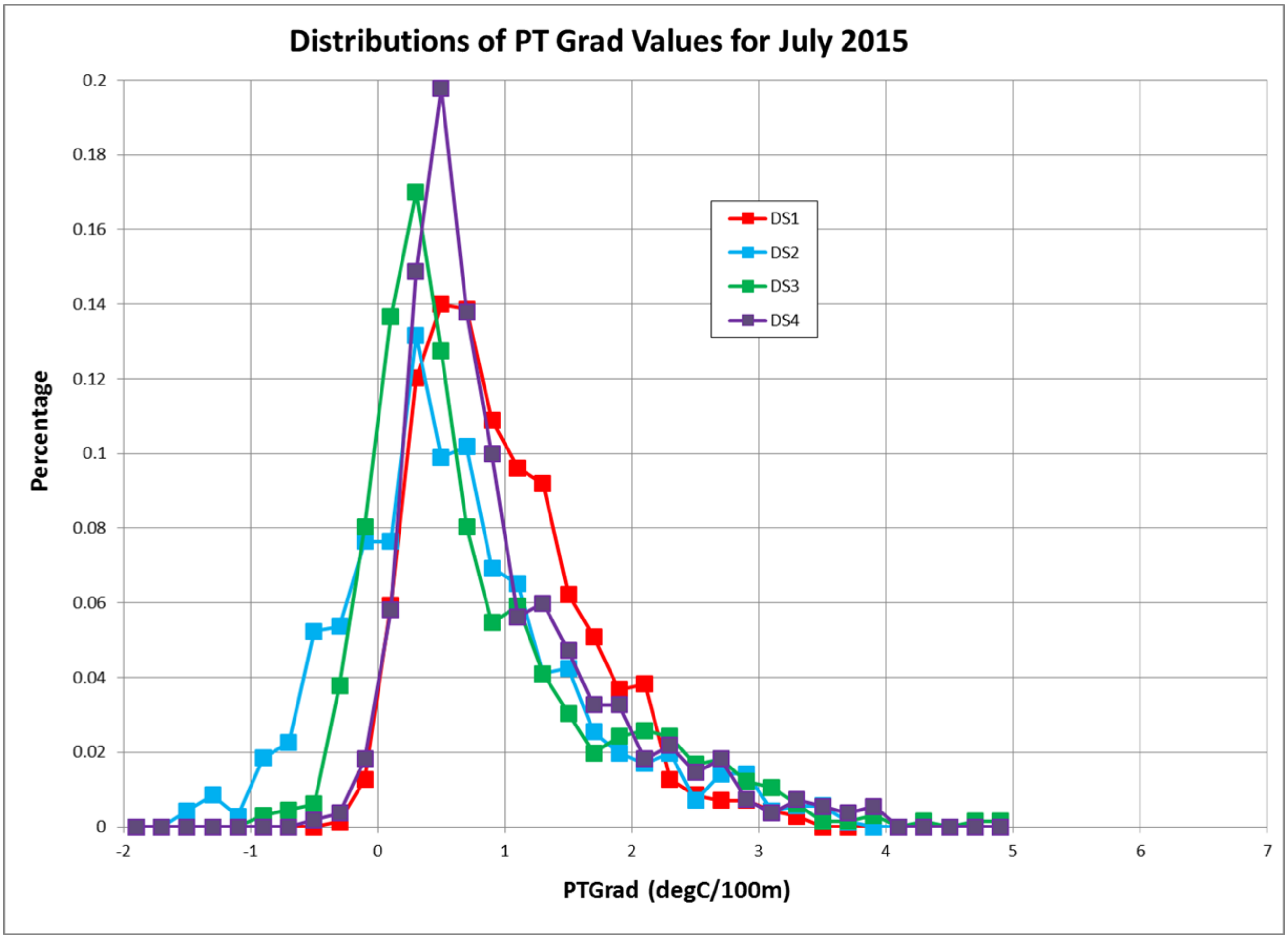



PT Gradients (DS2 vs DS3) for July 2015
DS2 PT Gradient (degC/100m)
DS3 PT Grad (degC/100m)
y = 0.6042x + 0.0955
R² = 0.3575
RMS Difference = 0.810
Average Abs Diff = 0.656
% Abs Diff < 1 = 78.2
5
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
4
5


PT Gradients (DS1 vs DS4) for July 2015
DS1 PT Grad (degC/100m)
DS4 PT Grad (degC/100m)
y = 0.6725x + 0.2067
R² = 0.7492
RMS Difference = 0.393
Average Abs Diff = 0.305
% Abs Diff < 1 = 98.1
5
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
4
5

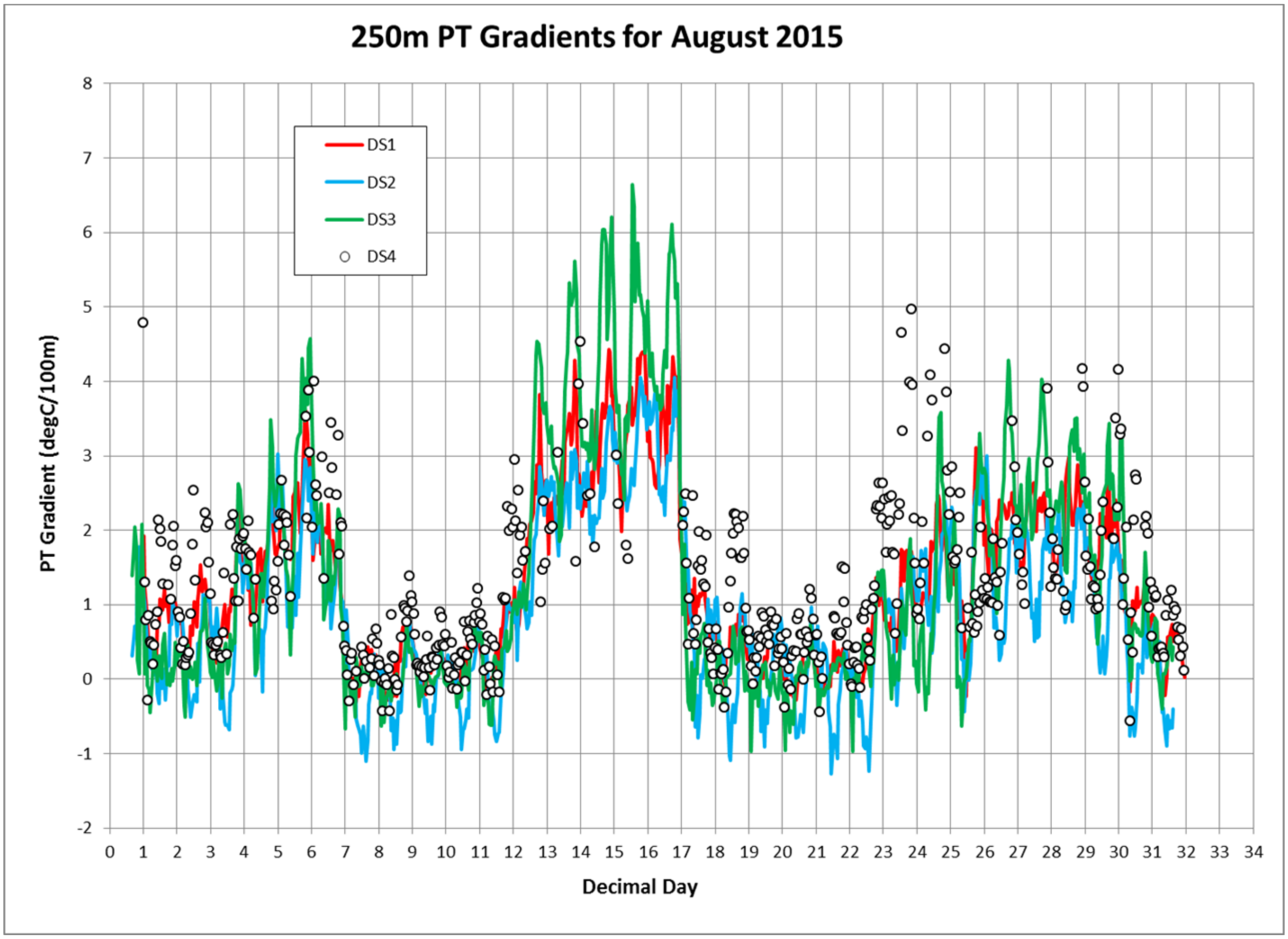

PT Gradients (DS2 vs DS4) for July 2015
DS2 PT Grad (degC/100m)
DS4 PT Grad (degC/100m)
y = 0.6763x - 0.1339
R² = 0.3629
RMS Difference = 0.842
Average Abs Diff = 0.639
% Abs Diff < 1 = 78.3

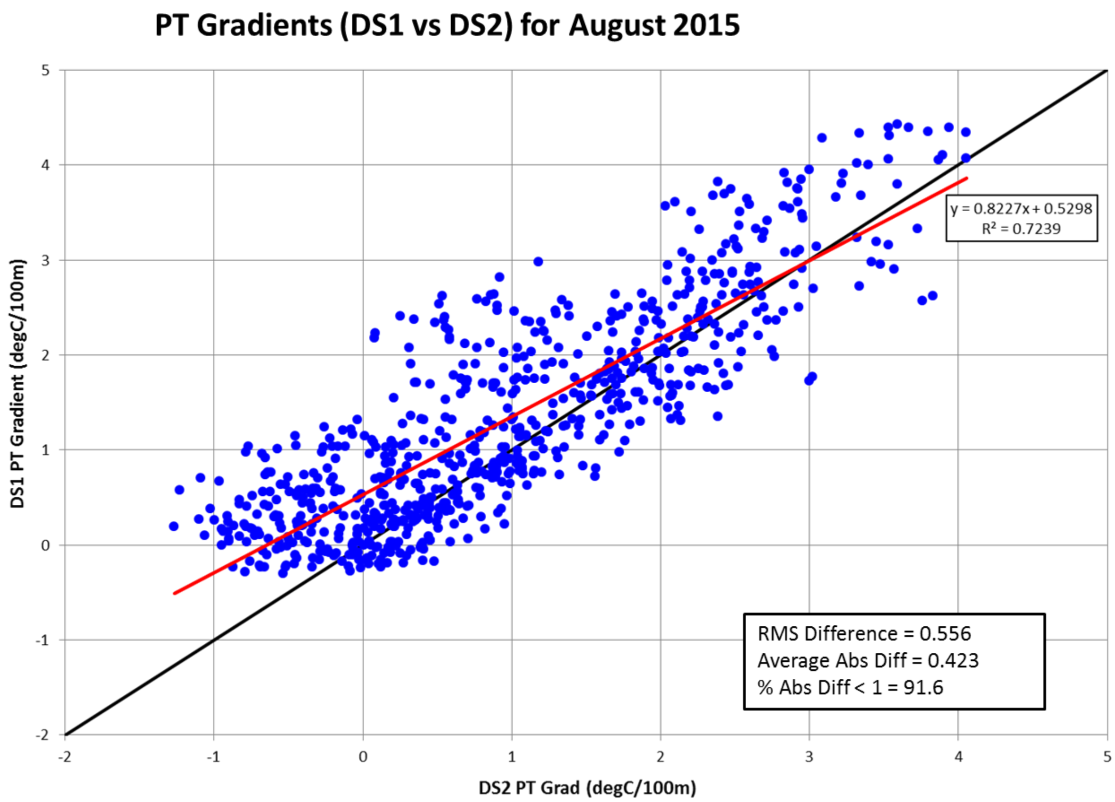

PT Gradients (DS3 vs DS4) for July 2015
DS3 PT Grad (degC/100m)
DS4 PT Grad (degC/100m)
y = 0.8042x - 0.1595
R² = 0.5873
RMS Difference = 0.633
Average Abs Diff = 0.487
% Abs Diff < 1 = 89.5

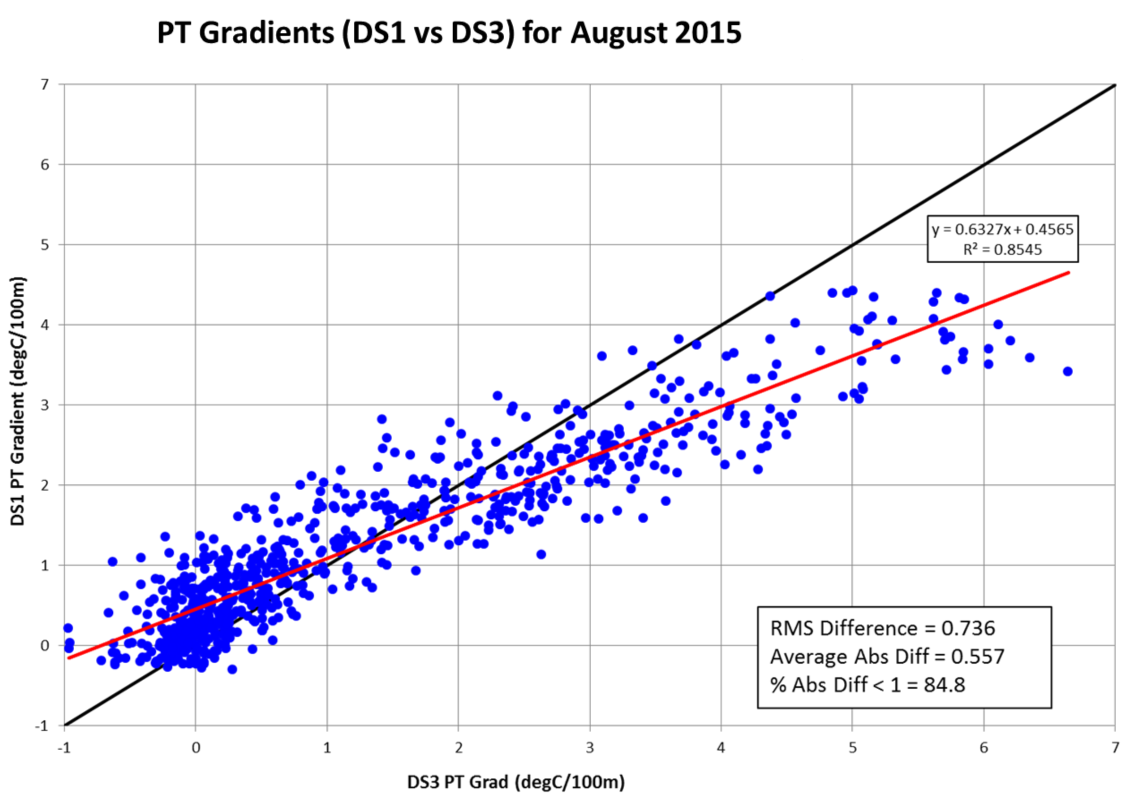


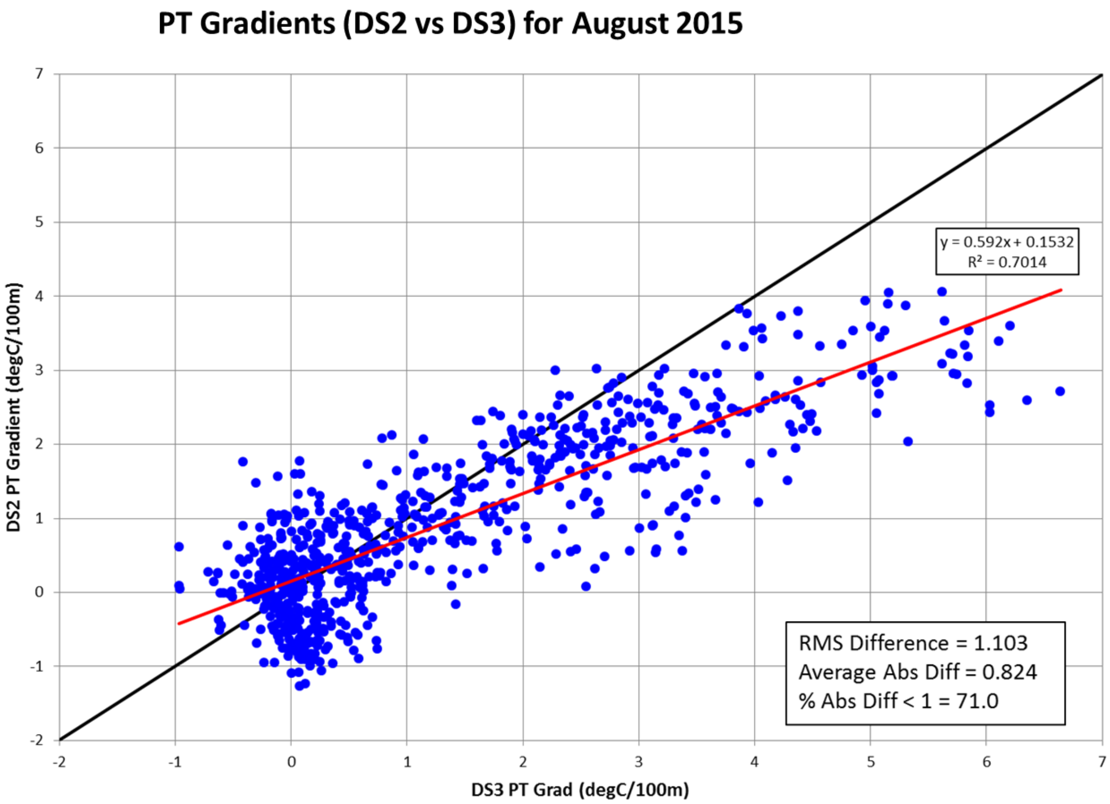
Distributions of PT Grad Values for July 2015
Percentage
PTGrad (degC/100m)
DS1
DS2
DS3
DS4
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-2
-1
0
1
2
3
4
5
6
7

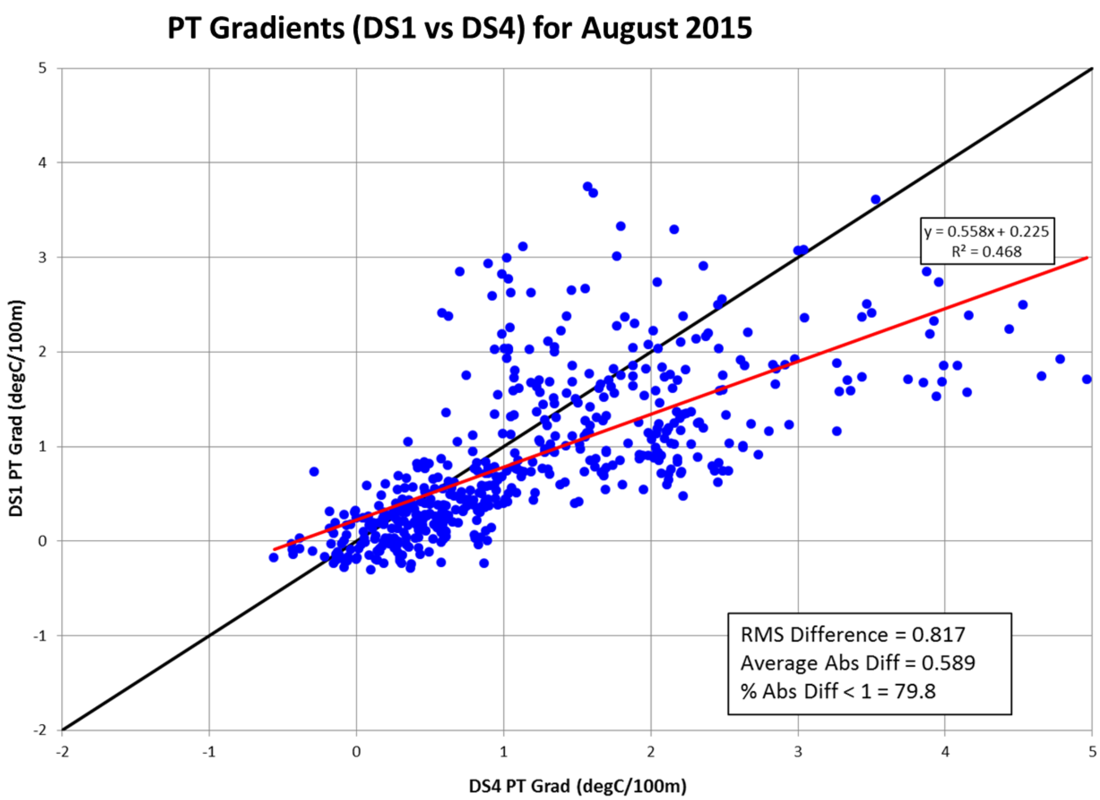
**Appendix C. PTG Plots for August 2015**



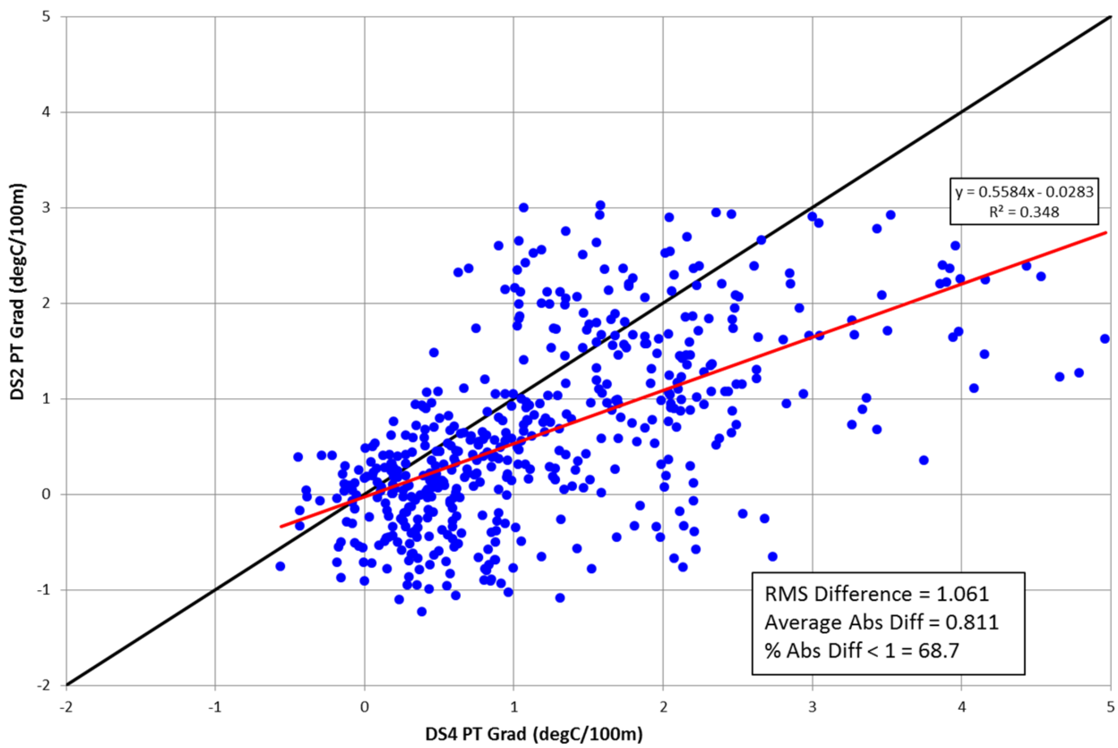

PT Gradients (DS1 vs DS2) for August 2015
DS1 PT Gradient (degC/100m)
DS2 PT Grad (degC/100m)
y = 0.8227x + 0.5298
R² = 0.7239
RMS Difference = 0.556
Average Abs Diff = 0.423
% Abs Diff < 1 = 91.6


PT Gradients (DS1 vs DS3) for August 2015
DS1 PT Gradient (degC/100m)
DS3 PT Grad (degC/100m)
y = 0.6327x + 0.4565
R² = 0.8545
RMS Difference = 0.736
Average Abs Diff = 0.557
% Abs Diff < 1 = 84.8

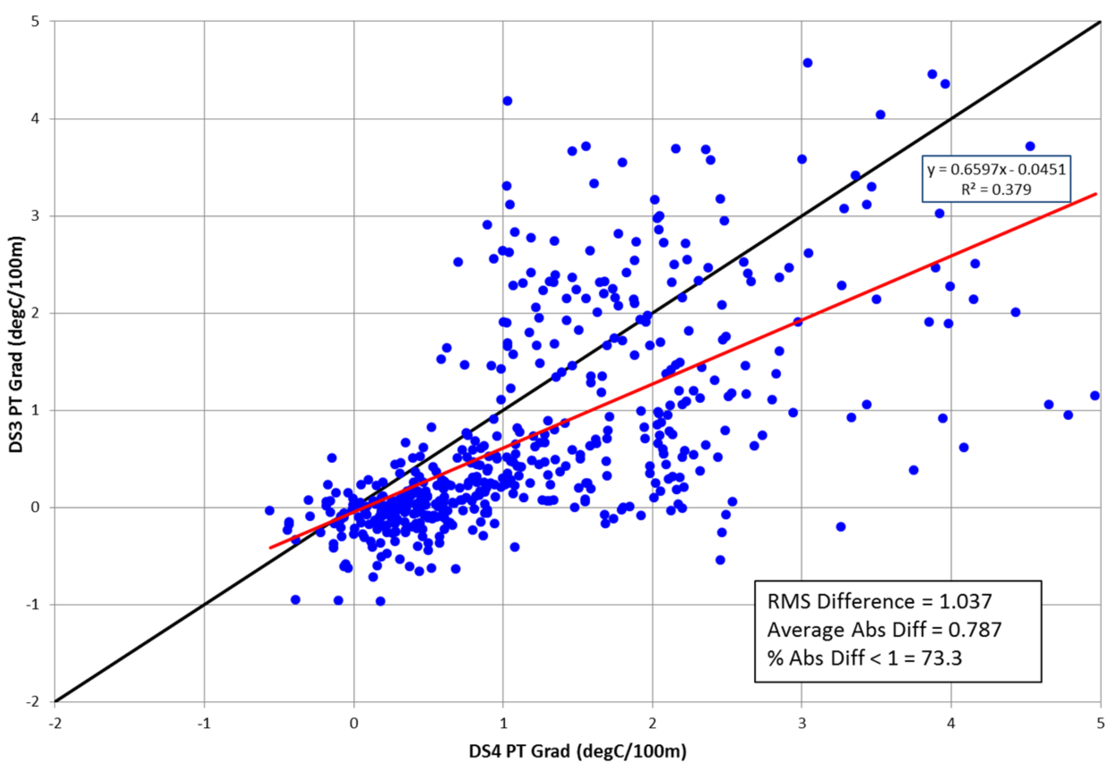

PT Gradients (DS2 vs DS3) for August 2015
y = 0.592x + 0.1532
R² = 0.7014
RMS Difference = 1.103
Average Abs Diff = 0.824
% Abs Diff < 1 = 71.0
DS2 PT Gradient (degC/100m)
DS3 PT Grad (degC/100m)

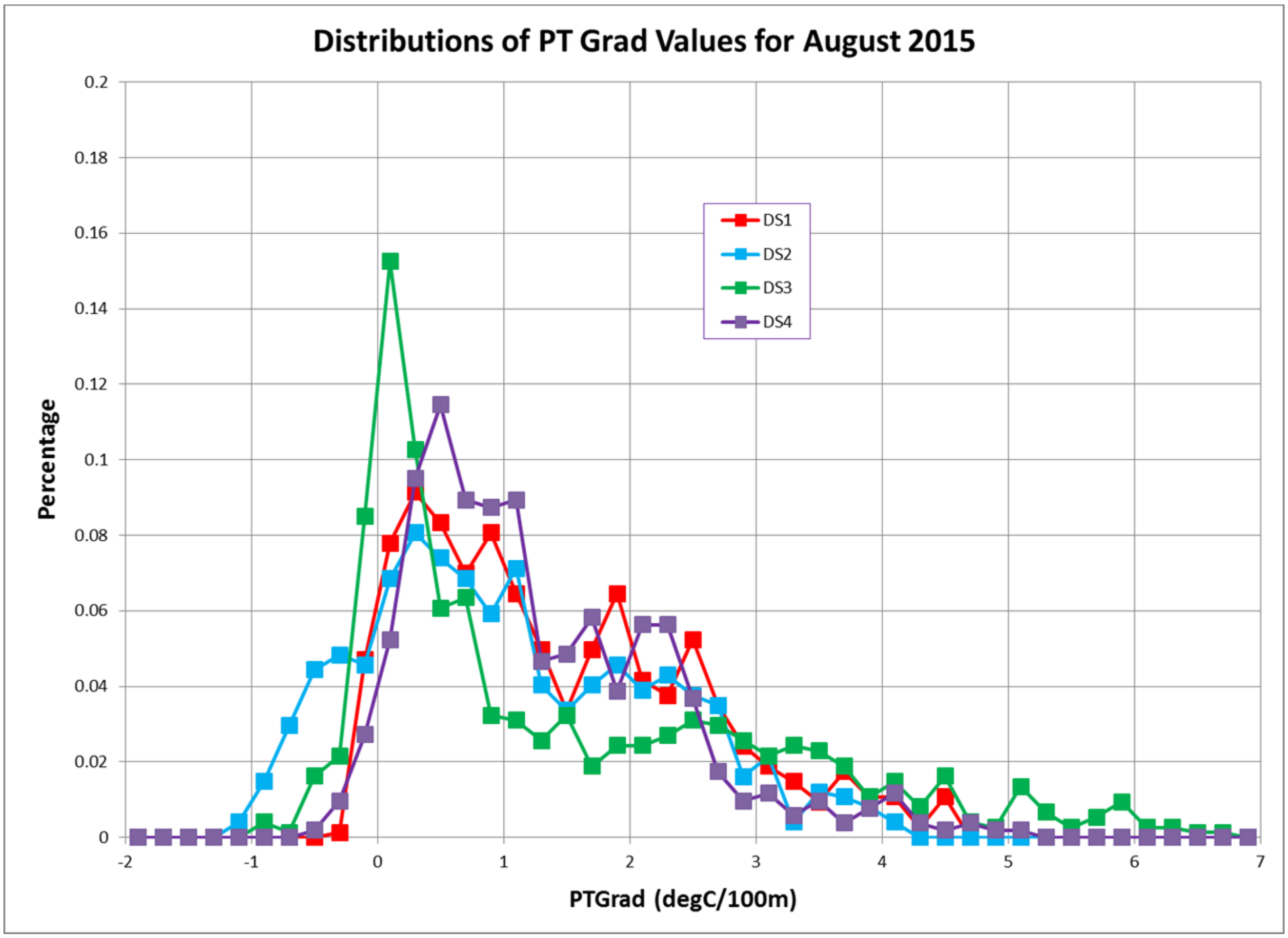

PT Gradients (DS1 vs DS4) for August 2015
y = 0.558x + 0.225
R² = 0.468
RMS Difference = 0.817
Average Abs Diff = 0.589
% Abs Diff < 1 = 79.8
DS1 PT Grad (degC/100m)
DS4 PT Grad (degC/100m)

## PT Gradients (DS2 vs DS4) for August 2015



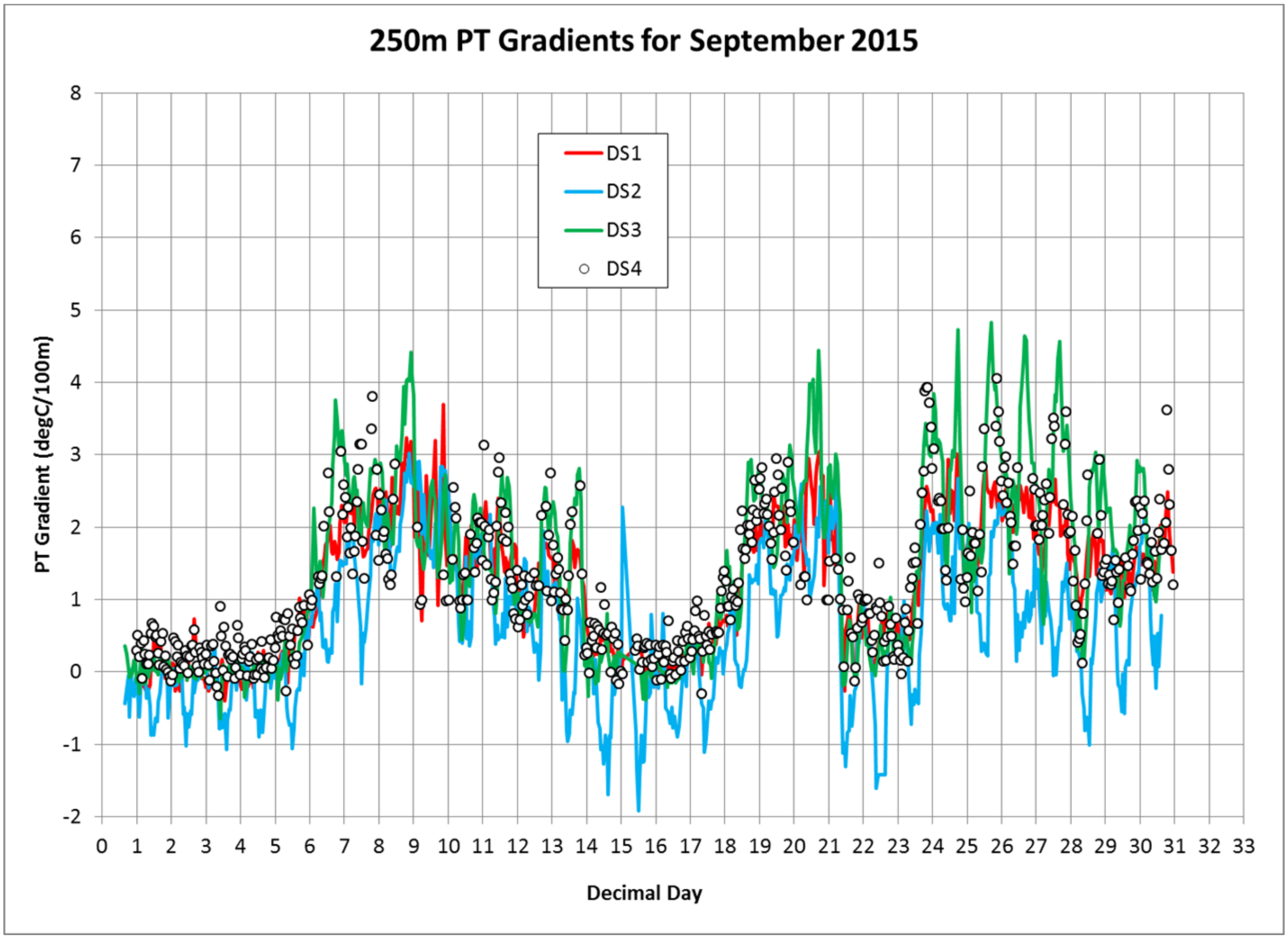

## PT Gradients (DS3 vs DS4) for August 2015

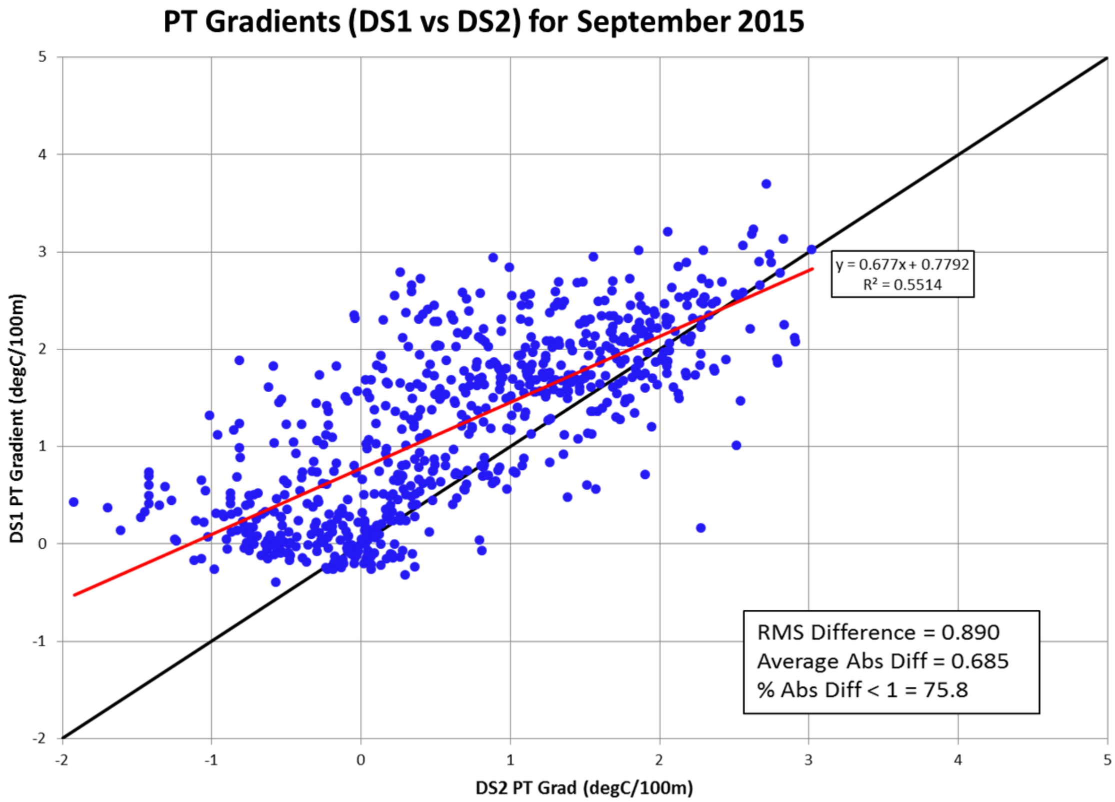




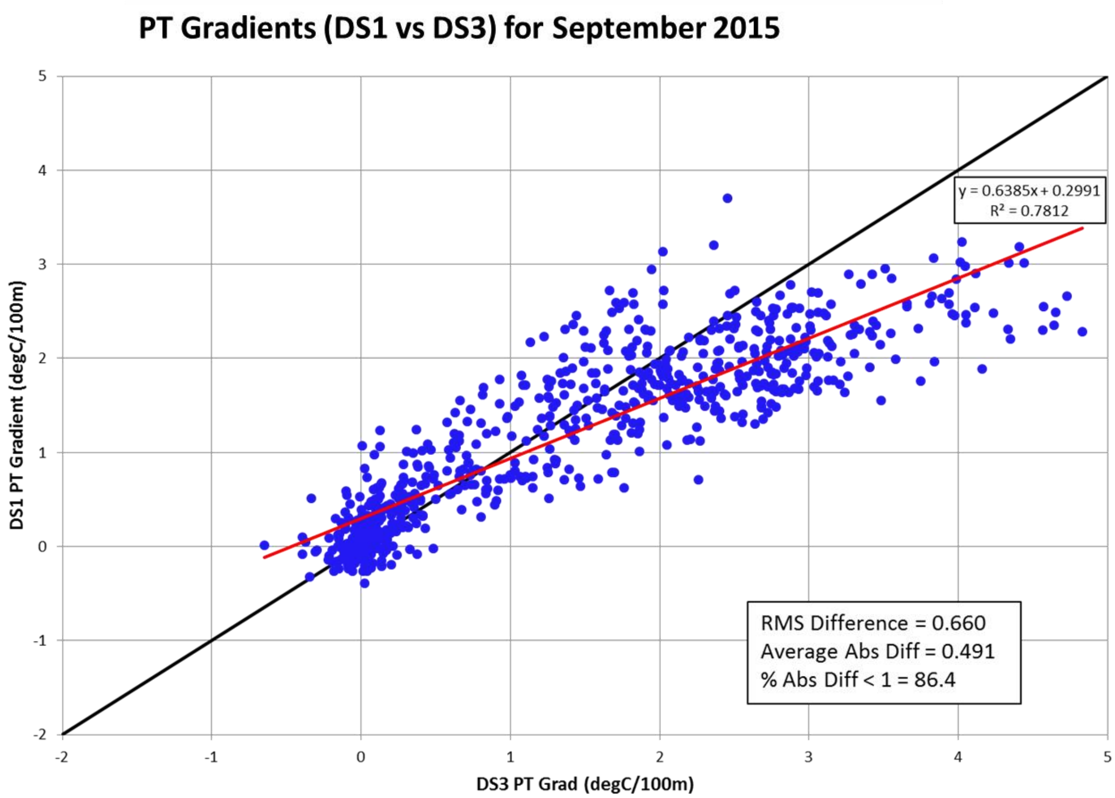
Distributions of PT Grad Values for August 2015
DS1
DS2
DS3
DS4
Percentage
PTGrad (degC/100m)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-2
-1
0
1
2
3
4
5
6
7

## Appendix D. PTG Plots for September 2015

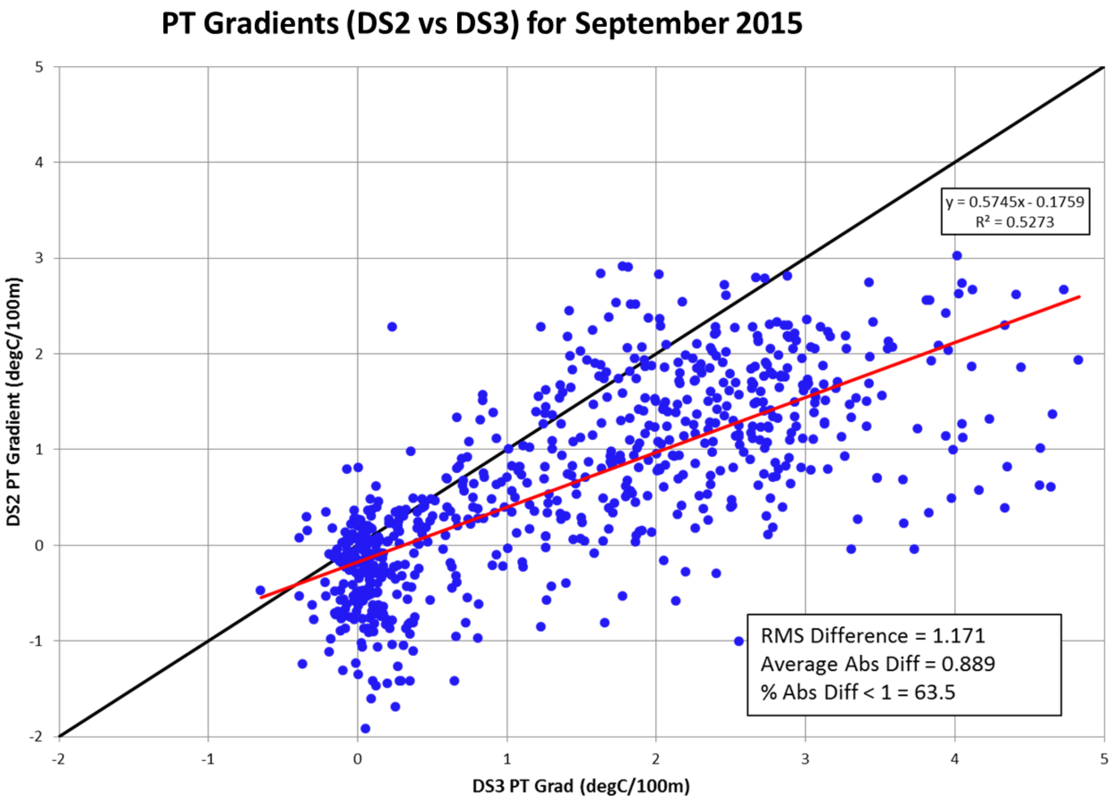


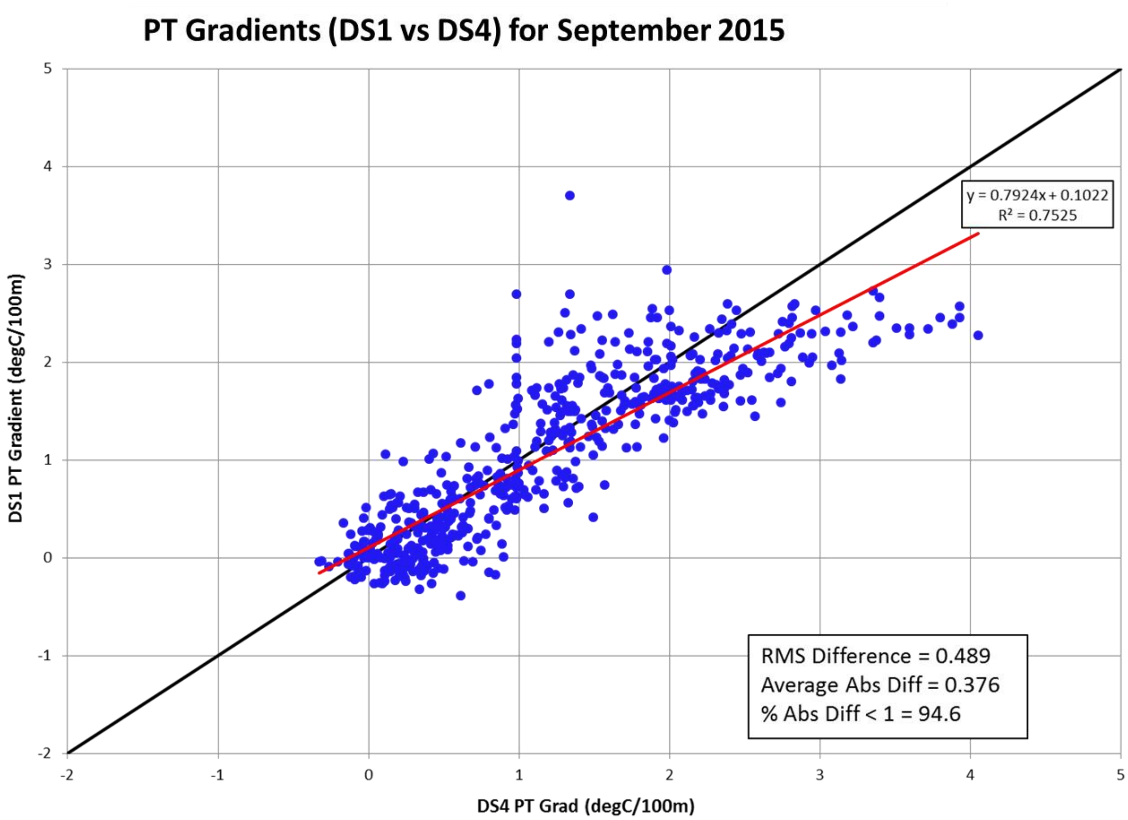


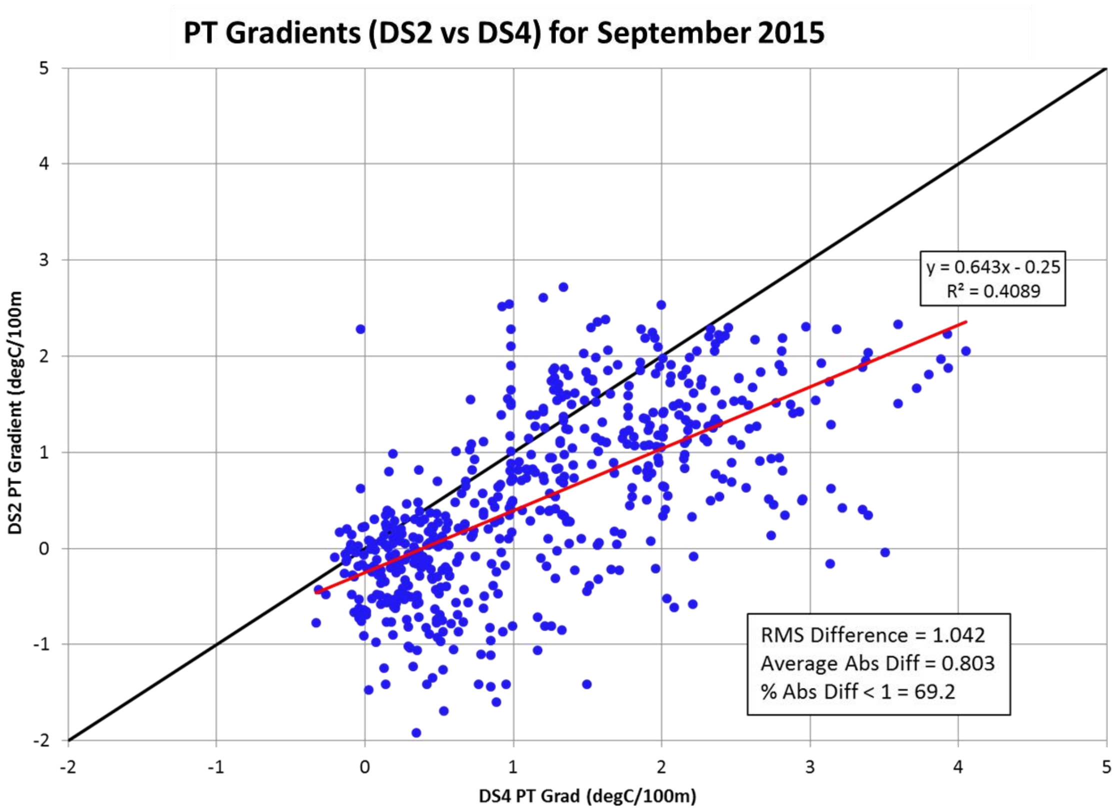
PT Gradients (DS1 vs DS2) for September 2015
y = 0.677x + 0.7792
R² = 0.5514
RMS Difference = 0.890
Average Abs Diff = 0.685
% Abs Diff < 1 = 75.8
DS1 PT Gradient (degC/100m)
DS2 PT Grad (degC/100m)

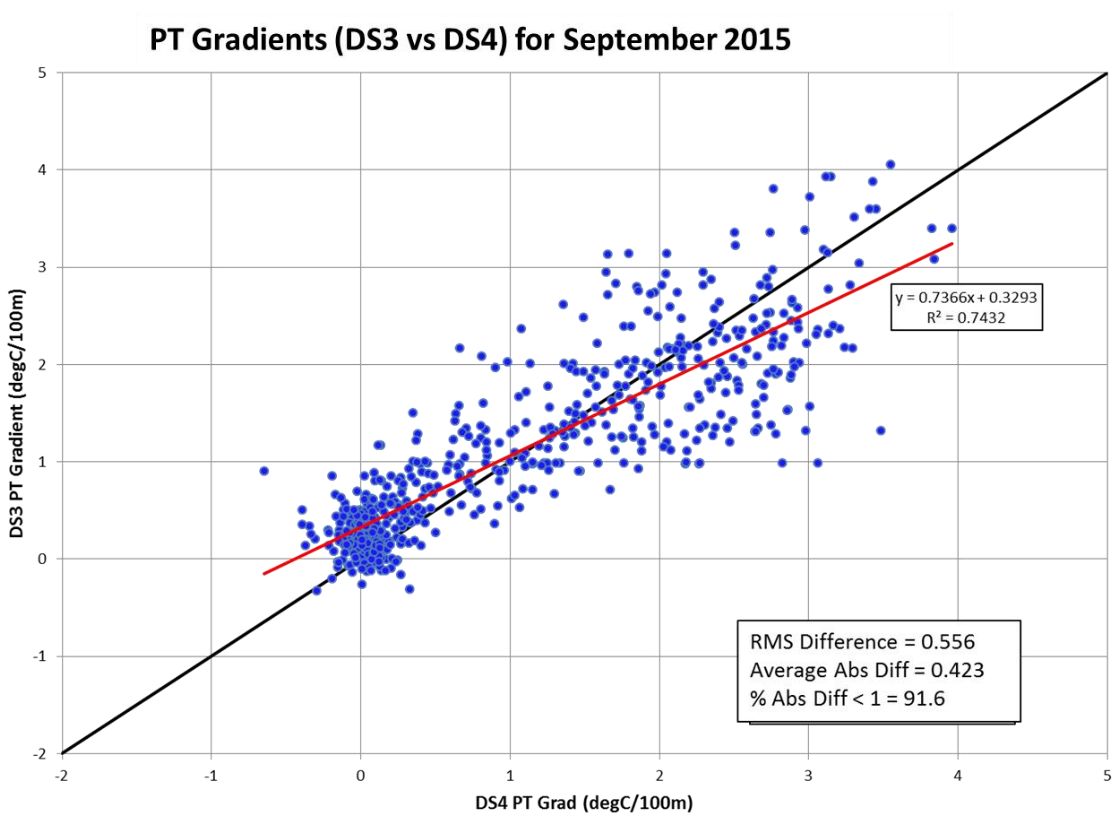



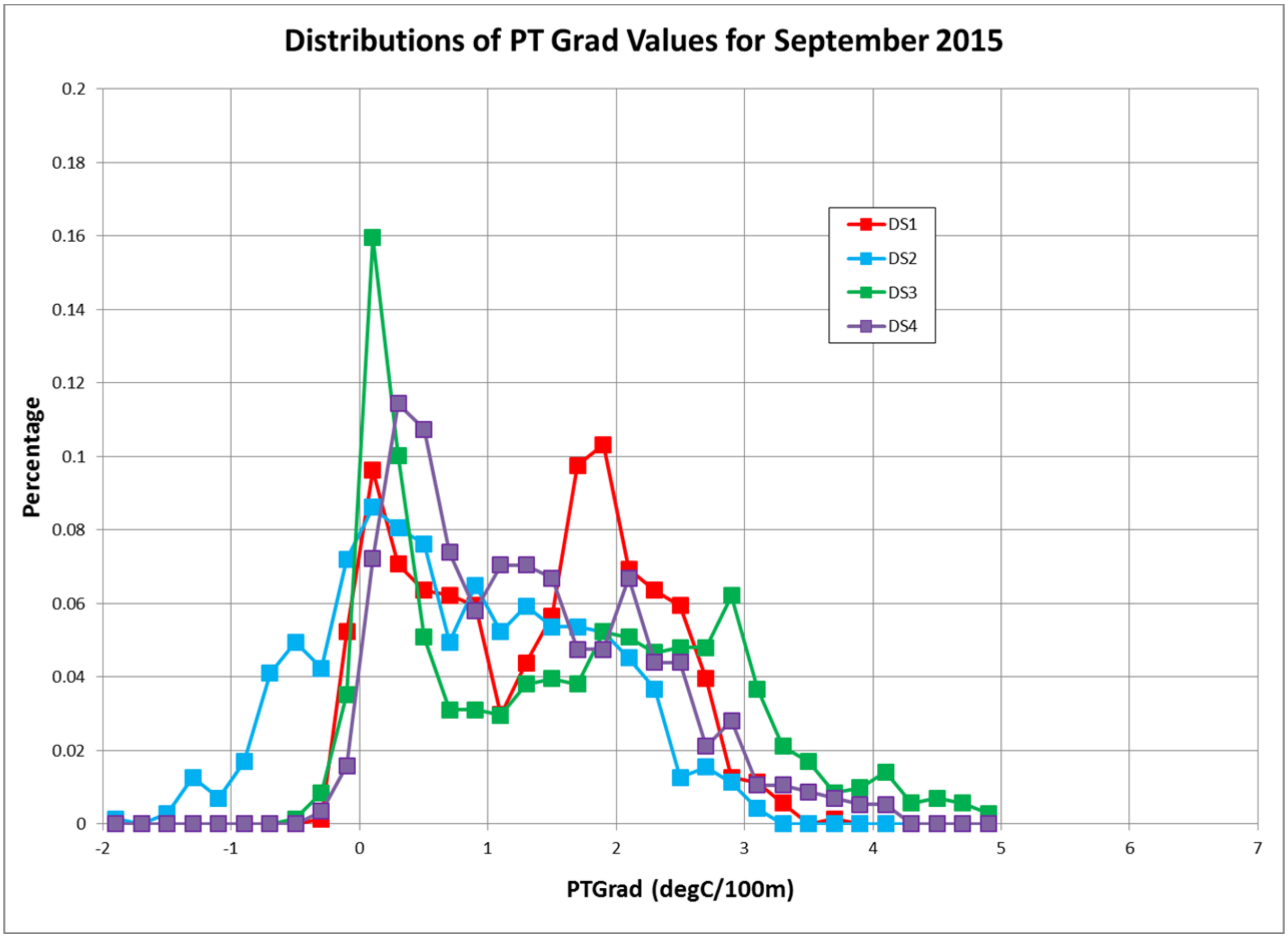
PT Gradients (DS1 vs DS3) for September 2015
y = 0.6385x + 0.2991
R² = 0.7812
RMS Difference = 0.660
Average Abs Diff = 0.491
% Abs Diff < 1 = 86.4
DS1 PT Gradient (degC/100m)
DS3 PT Grad (degC/100m)


PT Gradients (DS2 vs DS3) for September 2015
y = 0.5745x - 0.1759
R² = 0.5273
RMS Difference = 1.171
Average Abs Diff = 0.889
% Abs Diff < 1 = 63.5
DS2 PT Gradient (degC/100m)
DS3 PT Grad (degC/100m)


PT Gradients (DS1 vs DS4) for September 2015
y = 0.7924x + 0.1022
R² = 0.7525
RMS Difference = 0.489
Average Abs Diff = 0.376
% Abs Diff < 1 = 94.6
DS1 PT Gradient (degC/100m)
DS4 PT Grad (degC/100m)


PT Gradients (DS2 vs DS4) for September 2015
DS2 PT Gradient (degC/100m
DS4 PT Grad (degC/100m)
y = 0.643x - 0.25
R² = 0.4089
RMS Difference = 1.042
Average Abs Diff = 0.803
% Abs Diff < 1 = 69.2
5
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
4
5

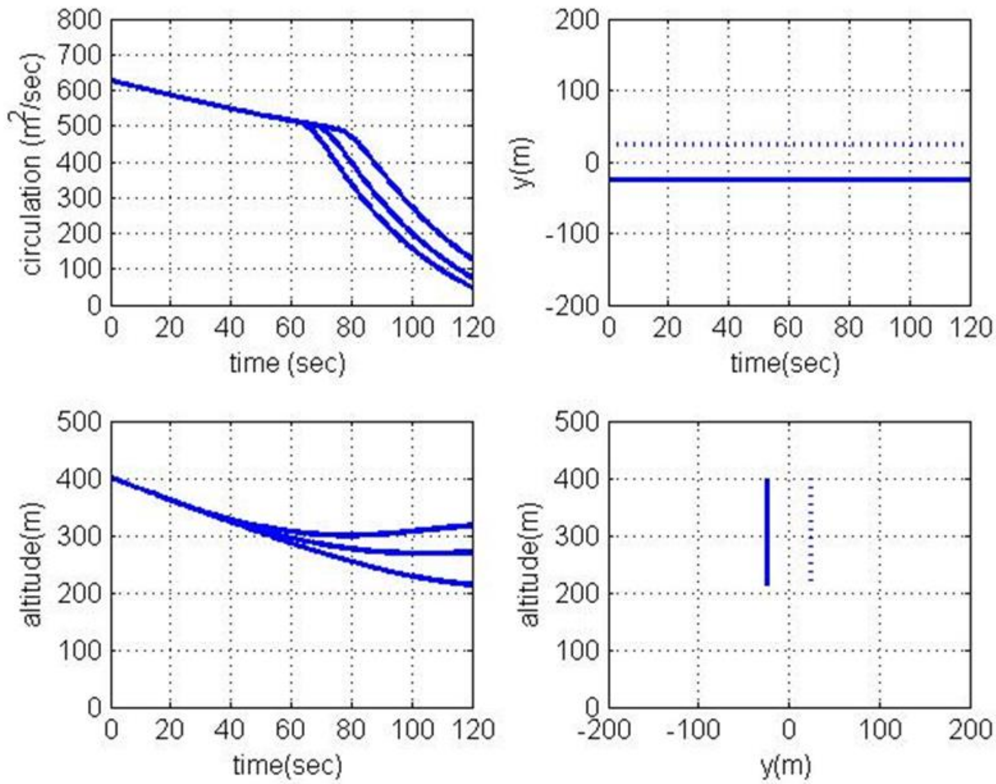

PT Gradients (DS3 vs DS4) for September 2015
DS3 PT Gradient (degC/100m)
DS4 PT Grad (degC/100m)
y = 0.7366x + 0.3293
R² = 0.7432
RMS Difference = 0.556
Average Abs Diff = 0.423
% Abs Diff < 1 = 91.6
5
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
4
5



Distributions of PT Grad Values for September 2015
Percentage
PTGrad (degC/100m)
DS1
DS2
DS3
DS4
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-2
-1
0
1
2
3
4
5
6
7

**Appendix E. Results for Model Runs**

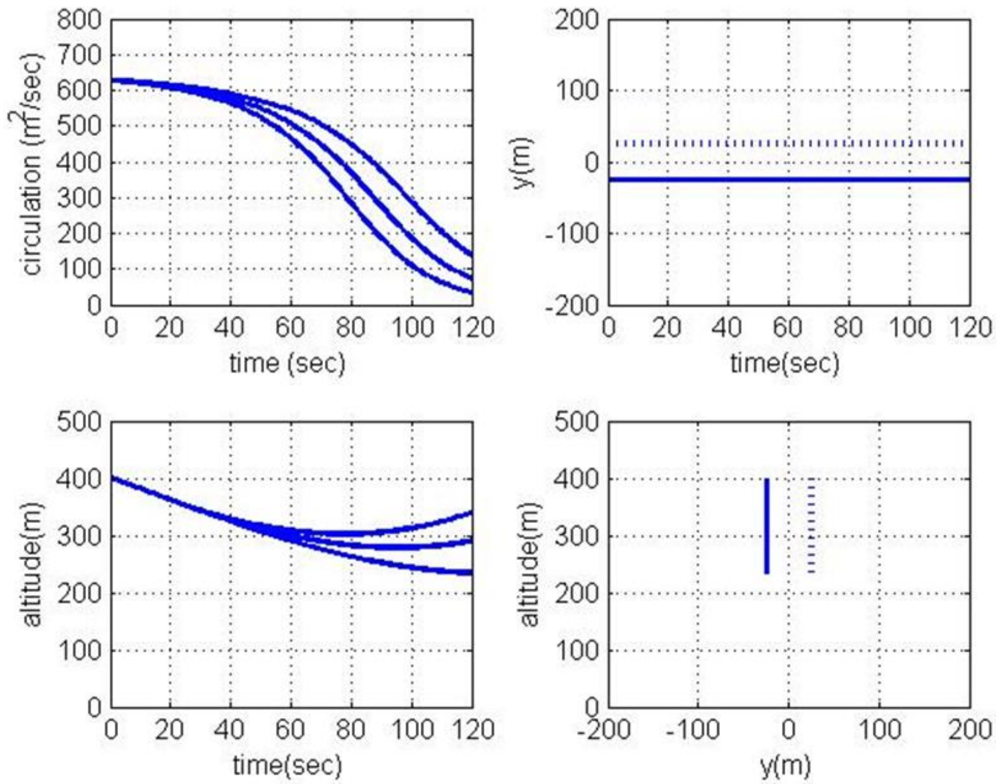
**D2P Results for PT Gradient of 1, 2 and 3 degC/100m**




**( Note: as PT Gradient ↑, circulation ↓ and descent ↑ )**

**The circulation and descent ranges at 120 sec were 87 $m^2$/sec and 103m, respectively.**

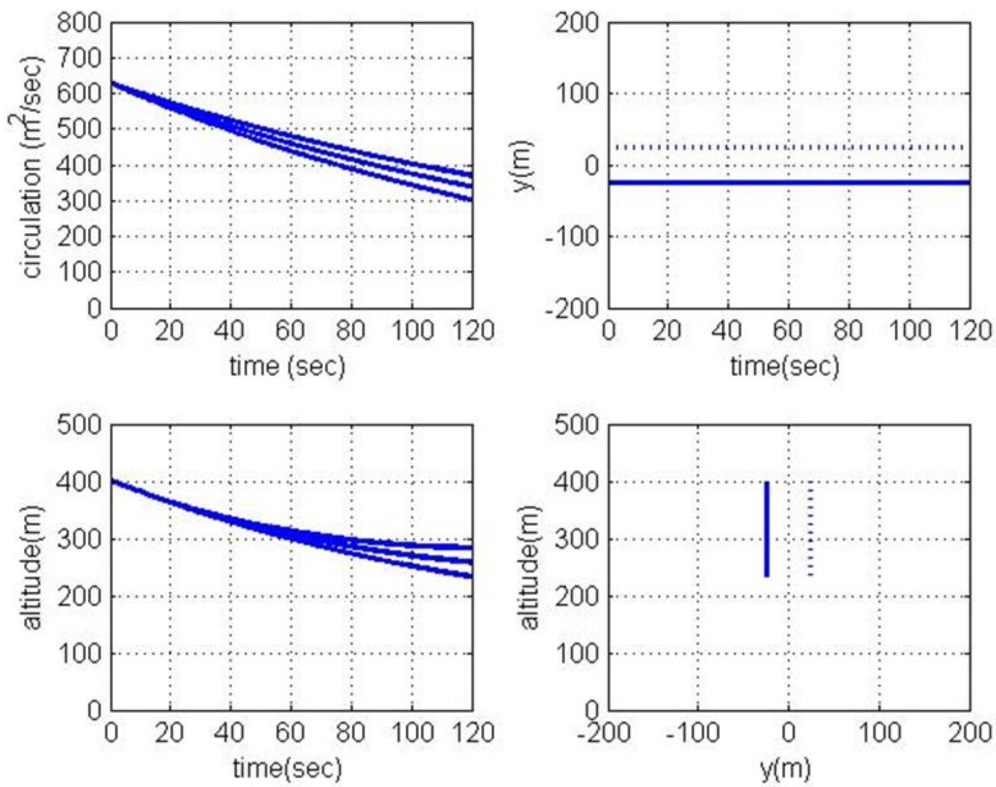
**TDAWP results for PT Gradient of 1, 2 and 3 degC/100m**




**( Note: as PT Gradient ↑, circulation ↓ and descent ↑ )**

**The circulation and descent ranges at 120 sec were 101 $m^2$/sec and 105m, respectively.**

**APA v3.8 Results for PT Gradient of 1, 2 and 3 degC/100m**




**( Note: as PT Gradient ↑, circulation ↓ and descent ↑ )**

**The circulation and descent ranges at 120 sec were 67 $m^2$/sec and 50m, respectively.**